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# **Fire Design of Single Storey Industrial Buildings**

**B W Cosgrove**

**Supervised by**

**Dr Andrew H Buchanan**

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School of Engineering  
University of Canterbury  
Private Bag 4800  
Christchurch, New Zealand

Phone 643 366-7001  
Fax 643 364-2758

## ABSTRACT

This report aims to establish a design methodology for meeting basic fire safety objectives within single storey industrial buildings using a 'common-sense' approach. A wide range of fire safety issues are addressed, ranging from environmental protection to life safety and structural performance. The emphasis is on meeting the performance requirements of the New Zealand Building Code for fire safety and hazard management. Given that industrial buildings are likely to fall into a high fire hazard category, alternative fire engineering design methods are deemed necessary for Building Code compliance.

Attention is also given to issues that are not part of Building Code requirements or acceptable solutions. A fire safety strategy is recommended for an industrial site, with the focus on establishing a level of 'acceptable loss'. A risk assessment provides the means to meet loss control objectives. This should form the basis for a new buildings' fire protection design, plus the on-going fire safety management programme.

Automatic alarms are considered essential for life safety and property protection, with sprinklers being the only method of controlling a fire within a typical industrial complex. The Fire Service cannot be expected to attack and suppress a fire from receiving an alarm call without sprinkler support. The Fire Service can, however, be expected to control the spread of fire to neighbouring property given certain conditional events work in their favour. The act of prewetting neighbouring combustible surfaces and thereby increasing the critical radiation intensity for pilot ignition, is considered very effective in preventing fire spread.

Increasing fire rating requirements for boundary walls based on withstanding equivalent fire severities for the 'design' fire, is considered overly conservative. A maximum rating of 4 hours is recommended for any boundary wall. This recommendation is based on maximum values used in overseas Codes and assumes that boundary walls are connected to primary support structures and adjoining wall panels, so that if they fail they collapse inwards as one complete unit.

The report provides a comprehensive list of conclusions that expand on the above overview, plus recommends areas for future research.



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## NOTATION

Symbol	Description	Units
$\alpha_t$	Power law fire growth co-efficient	$\text{kW/s}^2$
$\beta$	Co-efficient in critical exhaust rate equation: 1.3 for a vent near a wall; 1.8 for a vent distant from a wall.	$\text{kg/m}^3$
$\varepsilon$	Emissivity	(dimensionless)
$\varphi$	Angle between the receiver and flame point source.	(dimensionless)
$\theta$	Temp. of gases above ambient	K
$\theta_w$	Temperature difference between upper gas layer and upper walls.	K
$\sigma$	Stephan Boltzmann constant [ $56.7 \times 10^{-12} \text{ kW/m}^2\text{K}$ ]	$\text{kW/m}^2\text{K}$
$\rho_o$	Density of ambient air	$\text{kg/m}^3$
$\rho_T$	Density of air at temperature T	$\text{kg/m}^3$
$\phi$	Configuration factor	(dimensionless)
$\tau$	RTI time constant	(dimensionless)
$\lambda$	Thermal conductivity	$\text{W/mK}$
$A_w$	Area of wall	$\text{m}^2$
$A_e$	Area of detector element	$\text{m}^2$
$A_f$	Area of vertical window and door openings	$\text{m}^2$
$A_h$	Area of horizontal openings in roof	$\text{m}^2$
$A_I$	Area of inlets	$\text{m}^2$
$A_k$	Constant ( $= g/c\rho_o T_o$ )	$\text{m}^2/\text{kg}$
$A_s$	Specific surface area of fuel	$\text{m}^2$
$A_S$	Area of receiving surface	$\text{m}^2$

Symbol	Description	Units
$A_T$	Internal surface area of compartment	$m^2$
$A_v$	Area of vertical window and door openings	$m^2$
$A_v$	Area of vent	$m^2$
$A_v^*$	Effective area of vents	$m^2$
$(A_v)_{crit}$	Critical Vent Size	$m^2$
$A_w$	Area of vertical openings	$m^2$
$c$	Specific heat (of detector element)	$kJ/(kg \cdot ^\circ C)$
$C$	Constant for determining compartment temperatures	(dimensionless)
$C_d$	Coefficient of discharge	(dimensionless)
$C_p$	Specific heat of air at constant pressure	$kJ/kg \cdot K$
$C_P$	Wind pressure co-efficient	(dimensionless)
$d$	Depth of smoke layer	$m$
$D$	Distance between flame source and receiving surface	$m$
$D_f$	Width of flame	$m$
$e_f$	Fire Load	$MJ/m^2$
$E$	Energy released	$MJ$
$F$	Opening factor	$m^{1/2}$
$F_C$	Froude number	(dimensionless)
$g$	Acceleration due to gravity	$m/s^2$
$h$	Height of compartment	$m$
$h_a$	Calorific value of fuel	$MJ/kg$
$h_c$	Convective heat transfer co-efficient	$kW/m^2 \cdot ^\circ K$
$H$	Height above fire plume source	$m$
$H_f$	Height of firecell	$m$
$H_o$	Average height of openings	$m$
$l$	Flame height	$m$



Symbol	Description	Units
$m$	Lumped mass of detector element	kg
$m_{\text{air}}$	Burning rate for ventilation controlled fires	kg/s
$m_b$	Burning rate for wood in a ventilation controlled fire	kg/s
$m_F$	Burning rate of fuel	kg/s
$m_{\text{SF}}$	Specific burn rate of fuel	kg/s.m <sup>2</sup>
$M$	Smoke production rate	kg/s
$M_F$	Mass of fuel	kg
$M_{\text{crit}}$	Critical exhaust rate	kg/s
$M_e$	Mass extraction rate of venting, per unit area of ceiling	kg/m <sup>2</sup> s
$M_W$	Mass flow of water from sprinklers	kg/s
$N$	Number of exhaust points	(dimensionless)
$P$	Perimeter of fire	m
$P_B$	Buoyancy pressure	Pa
$P_F$	Fan back pressure	Pa
$P_I$	Pressure drop across inlet	Pa
$P_R$	Resultant pressure	Pa
$P_W$	Wind pressure	Pa
$Q_c$	Convective heat output of fire	kW
$Q_{\text{crit}}$	Heat value of fire that determines whether the fire is 'large' or 'small'	kW
$Q_{\text{CL}}$	Wall convection heat losses	kW
$Q_f$	Heat output of fire	kW
$Q_{\text{FO}}$	Minimum heat release rate for flashover	kW
$Q_L$	Heat loss out of compartment	kW
$Q_{\text{max}}$	Maximum heat output of a fire before failure conditions occur	kW
$Q_R$	Radiant heat flux received	kW

Symbol	Description	Units
$Q_{RL}$	Radiative heat losses	kW
$Q_T$	Total design heat load	kW
$Q_v$	Ventilation controlled rate of heat release	MW
$Q_{VL}$	Convective heat losses	kW
$Q_W$	Heat absorbed by water	kW
$r$	Radial distance from fire axis	m
$r_F$	Stoichiometric air/fuel ratio	(dimensionless)
$R$	Distance between point flame source and receiving surface	m
$RTI$	Response Time Index	$(m/s)^{1/2}$
$t$	Time from fire initiation	s or hrs - as noted
$t_1$	Detection time	s
$t_2$	Fire Service notification time	s
$t_3$	Fire Service travel time to incident	s
$t_4$	Fire Service access and search time	s
$t_5$	Fire Service attack commences	s
$t_a$	Avoidance time	s
$T_a$	Absolute temperature of ambient air	K
$T_{ae}$	Total evacuation time	s
$T_c$	Temperature of fire compartment	K
$t_d$	Detection time	s
$t_e$	Equivalent fire severity	min.
$t_E$	Escape time	s
$T_g$	Gas temperature	K
$t_g$	Standard fire growth time	s
$t_i$	'intervention' time	s
$t_l$	Transport time lag	s

Symbol	Description	Units
$t_p$	Preparation time	s
$T_r$	Rated temperature of detector	K
$t_r$	Response time	s
$t_r$	Fire resistance rating	min.
$t_s$	Time in which the heat output is 1 MW	s
$T_s$	Absolute temperature of smoke plume	K
$t_T$	Total burn time	s
$T_u$	Time to untenability	s
$\Delta T_{s-a}$	Smoke layer temperature above ambient	°C
$T_v$	Compartment temperature for a ventilation fire	°C
$\Delta T_{v-a}$	Vented smoke temperature above ambient	°C
$U$	Heat transfer coefficient	W/m <sup>2</sup> K
$u$	Gas velocity	m/s
$V_F$	Volumetric exhaust rate	m <sup>3</sup> /s
$V_v$	Volume flowrate through single orifice	m
$V_w$	Velocity of free wind stream	m/s
$w$	Factor for alarm device	(no unit)
$W$	Width of flaming source	m
$W_{eff}$	Response time factor - evacuation	(no unit)
$w_f$	Ventilation factor	m <sup>-0.3</sup>
$y$	Distance between floor and bottom of smoke layer under ceiling	m

# **FIRE DESIGN OF SINGLE STOREY INDUSTRIAL BUILDINGS**

## **PART 1 : FIRE SAFETY MANAGEMENT**

### **CONTENTS:**

- 1.0      Introduction**
- 2.0      Statistical Research**
- 3.0      Fire Safety Management**
- 4.0      Environmental Protection**

## 1.0 INTRODUCTION

Fire design for single storey industrial buildings has attracted particular interest due to the frequency of this type of construction, the high design fire loads, the relatively high risk of fire occurring, and the peculiar fire behaviour linked to rapid growth and probable roof collapse.

Industrial fires also present distinct cost problems. NFPA 1420 [1993] provides statistics showing that over a five year period in the United States 14.2% of reported loss fires occurred in storage facilities with the monetary loss equating to 38.3% of total costs. The cost also needs to be measured in terms of loss of business expectation, staff redeployment, and loss of intellectual property.

Spread of fire and environmental risk are other potential problems, whereas fatalities are reasonably uncommon [I.E. Aust, 1989]. Attention is therefore usually given to the physical effects of a fire. Given the potential outcomes and the likelihood of a serious fire, an owner needs to compare the costs against the benefits of enhanced protection. Again cost considerations need to include intangible factors such as intellectual property and business goodwill.

### 1.1 *N.Z. Building Code*

The New Zealand Building Code [BIA, 1991] has clear performance requirements for maintaining fire safety depending on the building use and fire hazard category, although it does not consider protection for the owner's property. The main fire safety objectives within the Code are:

1. Safeguarding people from injury or illness from a fire.
2. Facilitating Fire Service operations.
3. Protecting adjacent property from the effects of a fire.
4. Safeguarding the environment from adverse effects of fire.

For industrial buildings the minimum acceptable design solution in the Approved Documents is usually quite stringent due to the high combustible loading. Design for boundary walls requires specific fire engineering design if the fire hazard category is '4' (ie. the fire load energy density is greater than 1500 MJ/m<sup>2</sup>).

## **1.2 *Specific Fire Engineering Design***

The basis of specific fire engineering design is scenario analysis, where a large number of possible fire scenarios must be investigated. Such design must be carried out (and subsequently be reviewed) by suitably qualified professional fire engineers. Numerical calculations are available for individual components of the process, but the final assessment of safety is by opinion, not calculation, because the performance requirements of the code are not quantified (Cosgrove & Buchanan, 1996). This results in a number of different design strategies and solutions, without a quantifiable level of safety.

## **1.3 *Design Methodology***

The purpose of this document is to not only provide a design methodology for a specific fire engineering design, but also to investigate common problems with the fire design and management of single storey industrial buildings. The main issues addressed are:

- a) Reasons why fires in industrial buildings occur, and methods for minimising the loss.
- b) Identifying the responsibilities of a building owner for environmental protection, and establishing a risk assessment procedure.
- c) Developing a design methodology for possible fire scenarios, including an analysis of the effects of the fire in terms of occupant safety, structural performance and spread of fire.
- d) Providing an alternative design method for means of escape that includes behavioural response factors.
- e) Establishing the effect that active fire protection systems such as sprinklers and roof vents can have on fire, and looking at the interface options with support systems (ie. alarms, fire service callout, automatic doors, plant shutdown etc.).
- f) Reviewing the expected structural performance of primary support systems and boundary walls, with particular emphasis on what is a reasonable level of fire severity.

- g) Determining whether fire spread to neighbouring property will occur due to radiant heat transfer, especially given roof collapse and the effects of flames above boundary walls.
- h) Evaluating the minimum expected level of Fire Service performance, quantifying the effectiveness of water application on a fire, and assessing whether Fire Service intervention is a valid design tool.
- i) Introducing risk assessment as a design method.
- j) Promotion of loss control programmes on industrial sites, to minimise the possibility of a serious fire and the potential consequences. This includes promotion of pre-incident and contingency plans.
- k) Developing the concept of a complete fire safety design strategy where each fire design feature does not act independently but combines to create an overall site fire safety package.

#### **1.4 *Design Fire***

The most important aspect in a fire safety strategy development is the design fire. This needs to reflect the contained product and processes, and also allow for the following variables [Buchanan, 1994]:

- combustible load and distribution
- building configuration and construction
- fire detection, suppression and control equipment
- fuel growth rates, maximum heat release rates, smoke development and compartment temperature profiles
- building behaviour under fire conditions
- Fire Service response

#### **1.5 *Risk Assessment***

The tools available to model the interaction of these variables are relatively crude. Single storey industrial buildings may appear to be relatively simple to model since they are only one (large) compartment, but due to the size and the complexity of the fuel types and the unpredictable nature of a post-flashover fire (with probable roof collapse), accurate simulation is considered very difficult.

Risk assessment can be introduced as a method of predicting outcomes and it is expected that this will become more common in the future. Currently, however, there is inadequate guidance on what are acceptable levels of risk. One reference

even labelled the methods to quantify and verify fire safety levels as being ‘deeply unsatisfactory and even chaotic’[Magnusson et al, 1995].

This document aims to establish a design methodology for meeting basic fire safety objectives using a ‘common-sense’ approach. It is recognised that further research is required to substantiate design factors used, and that fire engineering design for single storey industrial buildings needs to be treated apart from other building types.



## 2.0 STATISTICAL RESEARCH

### 2.1 *Statistical Analysis : Fire Incidents 1988 -1994*

The following analysis is based on data sourced from the New Zealand Fire Service, through their Fire Information Recording System (FIRS). The information provided relates to the frequency of manufacturing and warehouse fires in New Zealand between January 1988 and November 1994 only. The objective of the analysis is:

- to understand the likely trends of fires in manufacturing or warehouse buildings, including:
  - industries most susceptible to fires
  - likely time of event
  - location and cause of fire
  - extent of damage expected
- to assess the high and low risk factors associated with this form of incident
- to study the trends associated with those fires which result in damage to the complete structure
- to estimate the probability of a manufacturing or warehouse fire occurring,

### 2.2 *Fire Incident Reporting System*

The New Zealand Fire Service maintain a Fire Incident Reporting System (NZFS, 1994), that records key information on every incident that they attend. Input fields include:

- incident date and time
- type of building and its use
- where and how the fire started
- extent of damage (flame, smoke and water)
- performance of automatic detection and suppression systems

The following discussion analyses data collected under this system, from January 1988 to November 1994. The data has been selected according to the following criteria:

1. Single storey industrial and warehouse complexes only (this therefore excludes complexes such as schools, hospitals, offices, residences etc.).
2. Exclusion of buildings less than 100 m<sup>2</sup> in floor area.
3. Exclusion of incidents caused by a false alarm.

A total of 626 industrial fire incidents have occurred throughout New Zealand in the 7 year period. Of this total number, 121 relate to warehouse facilities, and 505 to manufacturing complexes.

While these statistics are the best available, they do have some limitations that need to be recognised:

1. The total population of manufacturing and warehouse facilities in New Zealand is unknown, so the probability of a fire incident cannot be determined.
2. The recorded information is very generalised; while some incidents would appear to be similar, there are likely to be distinct differences in the actual events.
3. The input information has an undetermined margin of error.
4. Some incidents are not reported due to control by industry fire brigades.

While recognising that the data includes an undefined 'margin of error', the results do provide trends and a clear indication of the common features that are involved in typical manufacturing and warehouse fires.

### 2.3 Type of Occupancy

Figure 2.1 shows in pie graph format the percentage of incidents attended for various types of manufacturing occupancies. The outstanding statistic is the number of fires occurring at **wood and paper products facilities**. The total is 212 incidents, or 42%. This is clearly the highest risk group; the next largest grouping is furniture at 54 incidents (11%), which is also related to wood product facilities.

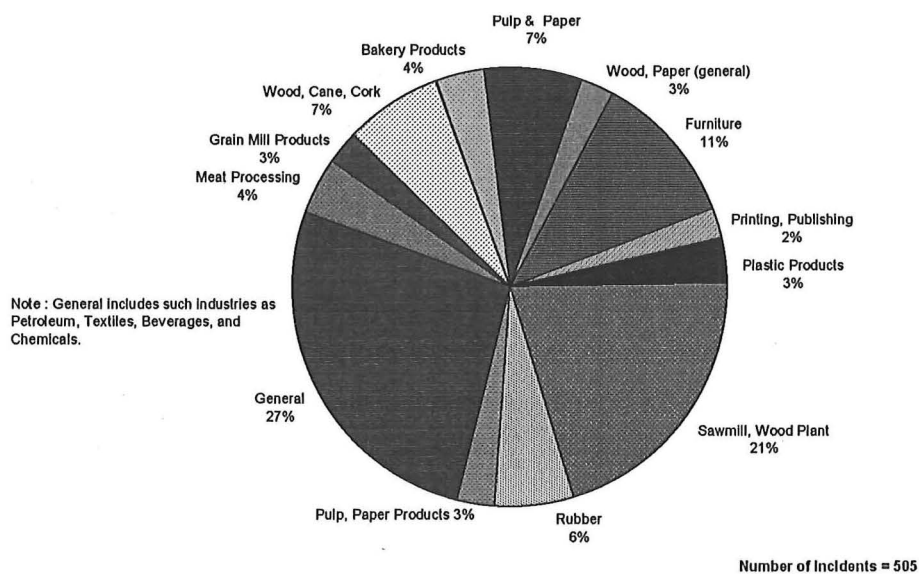


Figure 2.1 : Incidents Attended for Manufacturing Industries

Figure 2.2 shows incidents attended for various types of warehouse occupancies. This grouping is dominated by incidents occurring in general storage facilities, with a total of 33 incidents (27%). Wood and paper products is next with 25 incidents (21%).

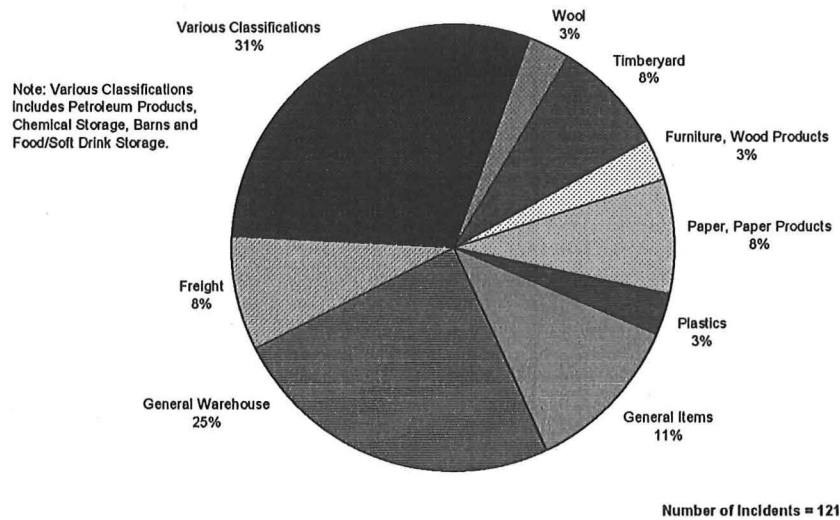


Figure 2.2 : Incidents Attended for Warehouse Storage.

Of note are occupancies that have had very low incident numbers over the last 7 years. They include:

#### Manufacturing:

- Beverages, Tobacco and Essential Oils (5 incidents)
- Chemical Manufacturers (8 incidents)
- Paints, Varnishes (4 incidents)
- Petroleum Refining (1 incident)

#### Warehousing:

- Cloth, Yarn Storage (2 incidents)
- Petroleum Products (0 incidents)
- Industrial Chemical Storage (0 incidents)
- Vehicle Storage (0 incidents)

Businesses associated with the traditional high risk operations, such as chemicals manufacture and petroleum refining, are clearly involved in fewer incidents than wood products. This is probably due to the tighter controls on their operations, coupled with the clear knowledge of the potential outcome of an incident plus the presence of industrial fire brigades.

## 2.4 Extent of Damage

Figure 2.3 reviews the extent of damage for all incidents, for both manufacturing and warehousing. The results indicate that generally either the fire is contained within the area of origin, or it will grow and involve the complete structure.

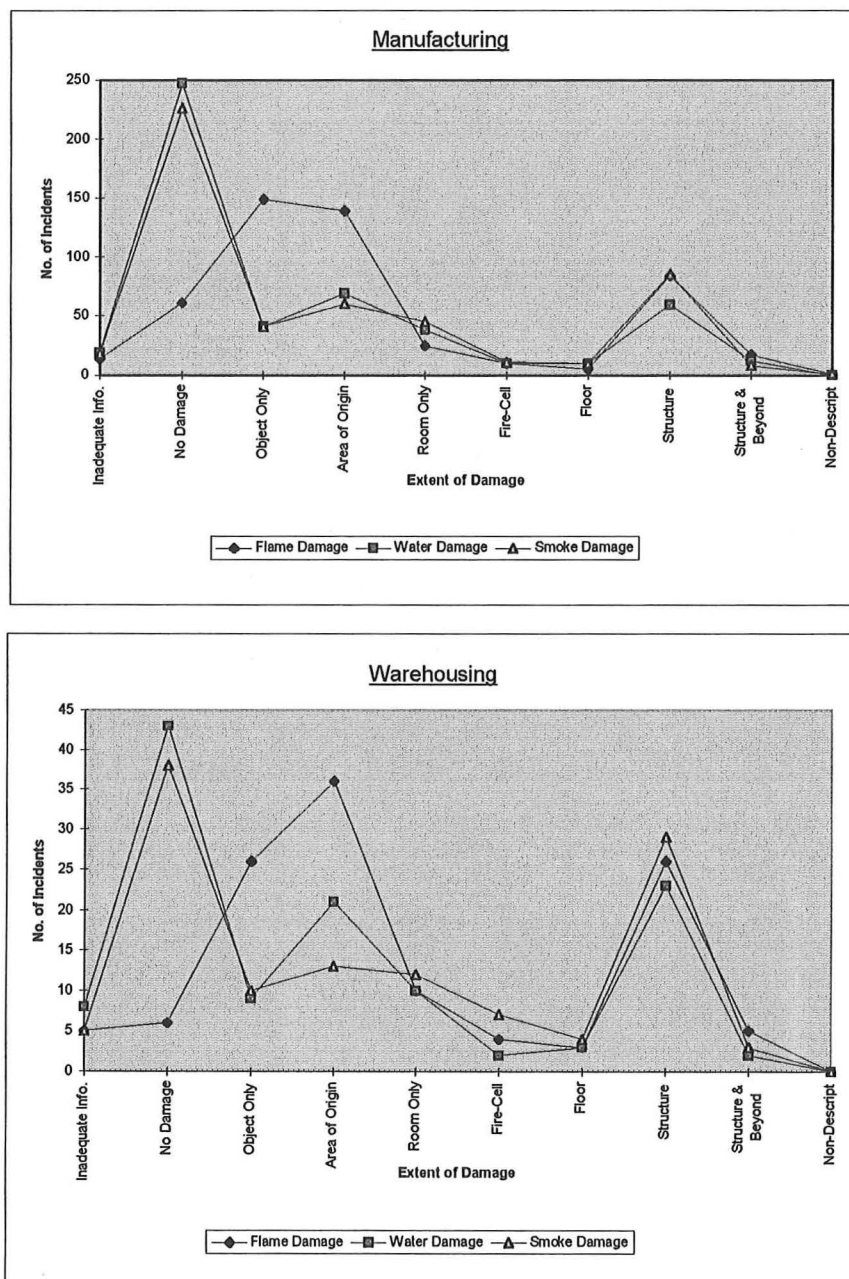


Figure 2.3 : Extent of Damage

In reality it is expected that most industrial buildings contain only one floor, and consist of only one fire-cell. If a fire does become out of control, then the whole structure would be likely to be damaged in some form. A review of British warehouse fires concluded that the degree of fire rated compartmentation is often inadequate to prevent large and expensive fires (Ward, 1985).

Figure 2.3 shows that if the fire is contained to area of origin then most damage will be caused by flames, while fires affecting the whole structure result in a combination of water, smoke and flame damage.

From this information, the subsequent charts are placed into two statistical groupings:

- statistics covering all incidents
- statistics covering total involvement incidents only. Total involvement means incidents resulting in some damage where this does not necessarily mean that the building is destroyed.

The trends associated with total involvement fires are considered more applicable to this study. A design procedure for single storey industrial buildings should aim to avoid major loss fires.

## 2.5 *Time of Incident*

Figures 2.4 and 2.5 provide a month and time of day comparison for the total 626 incidents. A yearly analysis was undertaken, but due to the study period being only 7 years it was considered that the sample period was too small to suggest any trends. The study by AEA (Hymes, Flynn 1992) concluded that the number of 'serious' storage fires in Britain had generally increased over the last 15 years. This was attributed to:

- larger and more modern warehouses with less compartmentation, more pallets and increased use of combustible wrappings.
- a general increase in the incidence of malicious fires ie. for reasons of arson, vandalism, fraud etc.

### 2.5.1 *Month of Year*

The monthly comparison in Figure 2.4, shows incidents peaking at different times of year, for both manufacturing and warehousing. The peak months are shown in Table 2.1:

Industry	Range of Incidents	Peak Months
Manufacturing	All Incidents	March, July November
	Total Involvement	March, June, November
Warehousing	All Incidents	March, June, October
	Total Involvement	February, June , October

Table 2.1 : Peak Incident Months

The reasons for the peak months are debatable. A chart was produced to see if there was any correlation between these peaks and the cause of ignition. One

theory for the March and June peaks is the advent of the end of the financial years, and fraudulent fires. The resulting chart showed that incendiary, or suspicious, causes are more frequent in these months. However, ignition caused through mechanical failure and misuse of ignited material was seen to be also very high.

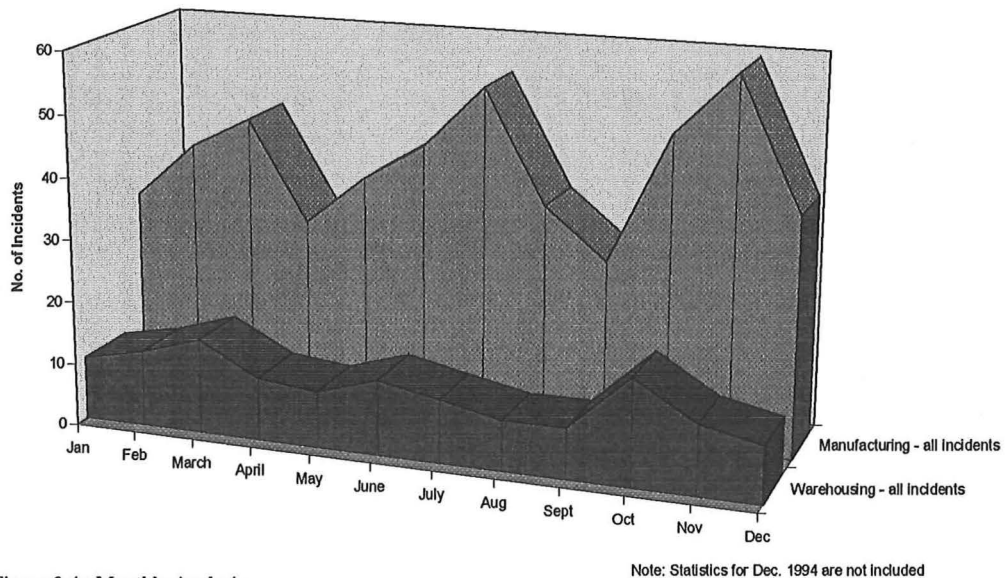


Figure 2.4 : Monthly Analysis

Note: Statistics for Dec. 1994 are not included

There does not appear to be any clear indicator as to why these months should peak, or why January, April and September are low incidence months. The only message from these results is the need for industrial businesses to be more vigilant during the peak months.

### 2.5.2 Time of Day

Figure 2.5 records alarm times during a 24 hour day for all incidents and total involvement incidents only. The noticeable trends for **all incidents**, are:

1. Between 1am -7am there is a relatively low number of incidents.
2. From 7am to 6pm there is a gradual increase in incident numbers, to reach a peak between 12-1pm, and then decline to a relatively constant number after 6pm.
3. Between 6pm-1am the incident numbers range between 2-2.5 times the number in the early morning hours (1am-7am).

These results indicate that incidents are more likely to occur during the daylight and evening hours. Given that a high proportion of fires are due to plant failure or deficiency factors, the correlation to alarm times support the theory that most fires are instigated as a result of occupancy.

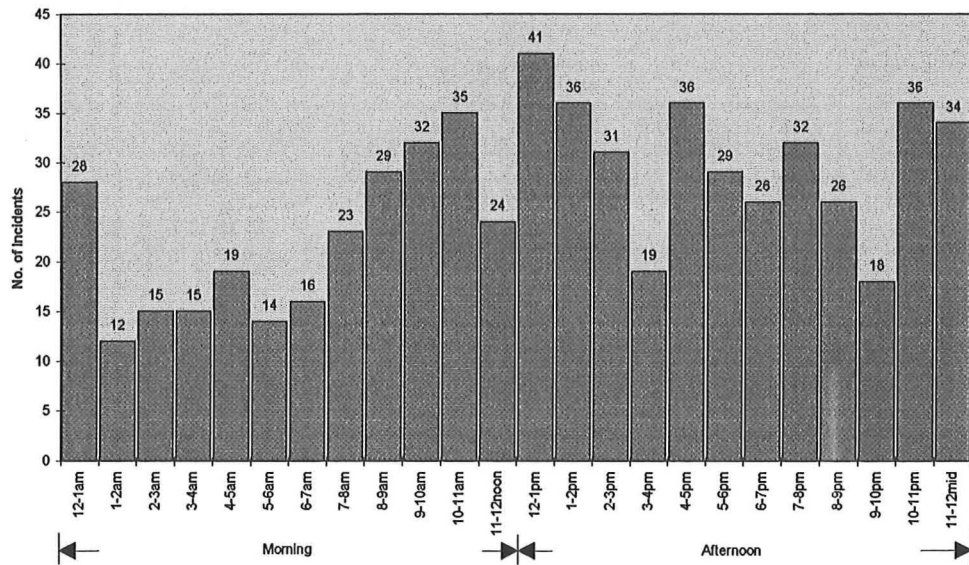


Figure 2.5 : Alarm Times

Alarm times for **total involvement incidents** only, show a peak period between 7pm and 1am. The majority of fires occur between 6pm and 6am (66%); this is in close correlation with the results from the AEA study (Hymes, Flynn 1992) which showed that 62% of 'serious' warehouse fires occurred within these hours. These results indicate that the cause of fire and method of alarm may have a strong influence on the extent of damage.

## 2.6 Method of Alarm

Figure 2.6 was created to investigate the possibility of a link between method of alarm and extent of damage.

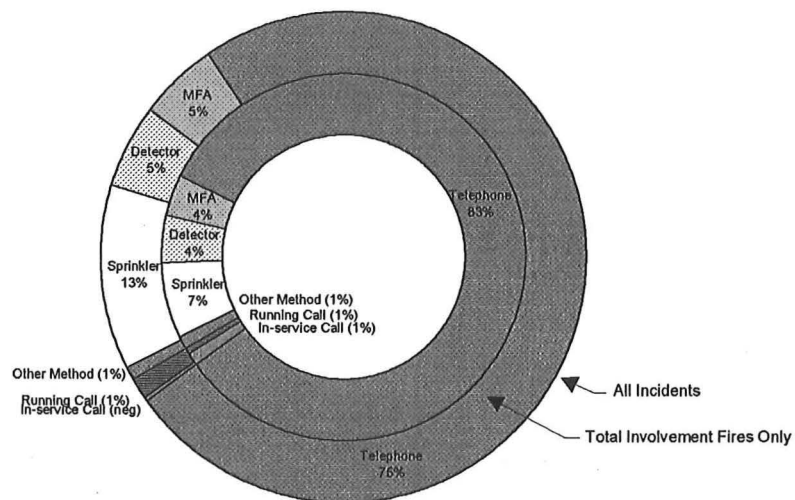


Figure 2.6 : Method of Alarm

In reviewing whether fires resulting in major damage were attributable to the lack of automatic detection systems, it was found that 83% of these incidents were alerted to the NZFS by telephone. This compared to 75% for all incidents.

Fires occurring during working hours are expected to be detected at an early stage. The fact that most Total Involvement fires occur out of hours, shows that without some form of early detection (ie. automatic detection systems), a fire can develop into a major incident. Automatic detection systems appear to be absent mainly because NZ building codes have not required them in single storey industrial buildings.

## 2.7 Area of Fire Origin

Figures 2.7 and 2.8 show the area of fire origin for manufacturing and warehousing facilities, with a distinction again made between all incidents and total involvement incidents only. The predominant areas are shown in Table 2.2:

Industry	Range of Incidents	Most Common Area of Fire Origin	Percentage of Incidents
Manufacturing	All Incidents	Technical Areas Service Areas	43% 20%
Manufacturing	Total Involvement	Technical Areas Service Areas	35% 20%
Warehousing	All Incidents	Storage Areas Structural Areas	50% 21%
Warehousing	Total Involvement	Storage Areas Staff Areas	59% 15%

Table 2.2 Common Areas of Fire Origin

As expected, most fires started in the technical (or processing) areas in manufacturing buildings, and in the storage areas for warehouses. This trend continues for those fires causing total damage. The study by AEA (Hymes, Flynn 1992) determined that for warehouses, the highest risk for fire outbreak by either accidental or malicious ignition were ramps and loading bays. Reasons given for this outcome were:

- site of most warehouse operations
- lower level of control for segregating and handling goods
- accumulation of general rubbish
- fire safety control, such as no smoking, difficult to control due to the presence of non-company personnel.



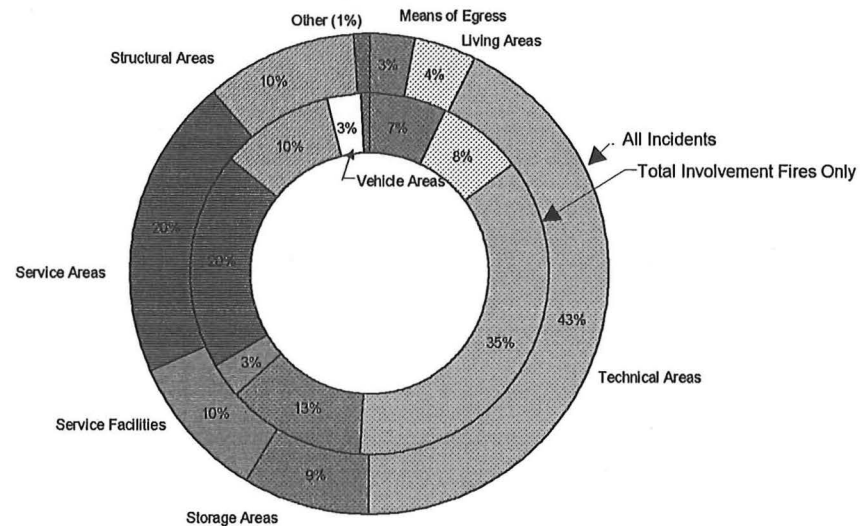


Figure 2.7 : Area of Fire Origin in Manufacturing Facilities.

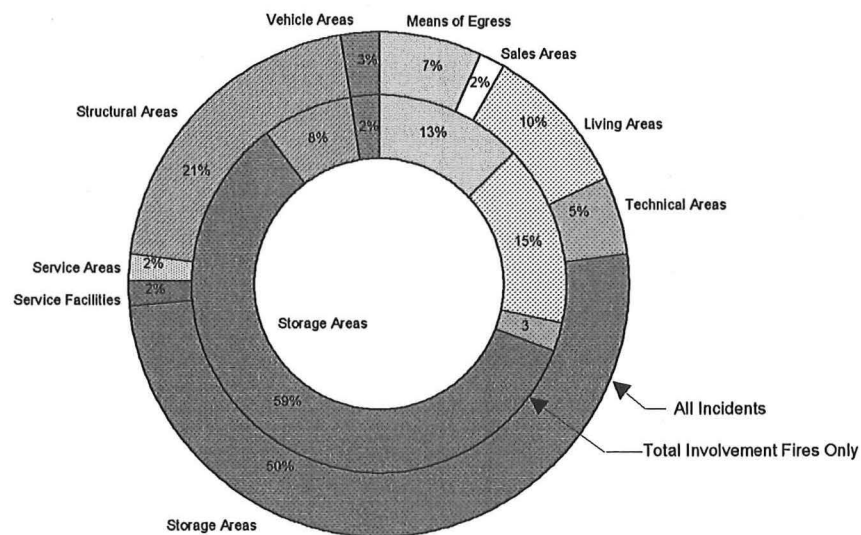


Figure 2.8 : Area of Fire Origin in Warehousing Facilities.

In comparing the data between manufacturing and warehousing, it is interesting to note that the service areas and facilities in manufacturing buildings are the source area for 30% of incidents, yet only 4% for warehousing. This highlights the distinct difference in service requirements between a processing facility and a storage building.

The final point of note is that there is not much variation in the area of fire origin between the results for all incidents, and total involvement fires only.

## 2.8 Cause of Ignition

This information was reviewed in the same manner as the Area of Fire Origin data. Figures 2.9 and 2.10 show the various causes in general classifications, with differentiation between manufacturing and warehousing, and **all incidents** and **total involvement only**.

The most notable indicator to come from these figures, is that an incendiary is by far the predominant cause of ignition for total involvement fires. The definition for incendiary given by the Fire Service is fires that are either started unlawfully, or deliberately set but deemed 'lawful'. At most incidents the noted cause for the incendiary in the FIRS is unlawful or suspicious.

In terms of a design process, the large range of ignition sources indicates that no prediction can be made for how a fire is likely to ignite and spread.

Summarising the principle causes:

Industry	Range of Incidents	Cause of Ignition	Percentage of Incidents
Manufacturing	All Incidents	Mechanical Failure	25%
		Misuse of Heat	16%
		Operational Deficiency	15%
Manufacturing	Total Involvement	Incendiary	31%
		Mechanical Failure	22%
		Other Factors	16%
Warehousing	All Incidents	Incendiary	40%
		Misuse of Heat	23%
		Mechanical Failure	15%
Warehousing	Total Involvement	Incendiary	61%
		Misuse of Heat	15%
		Mechanical Failure	8%

Table 2.3 Cause of Ignition

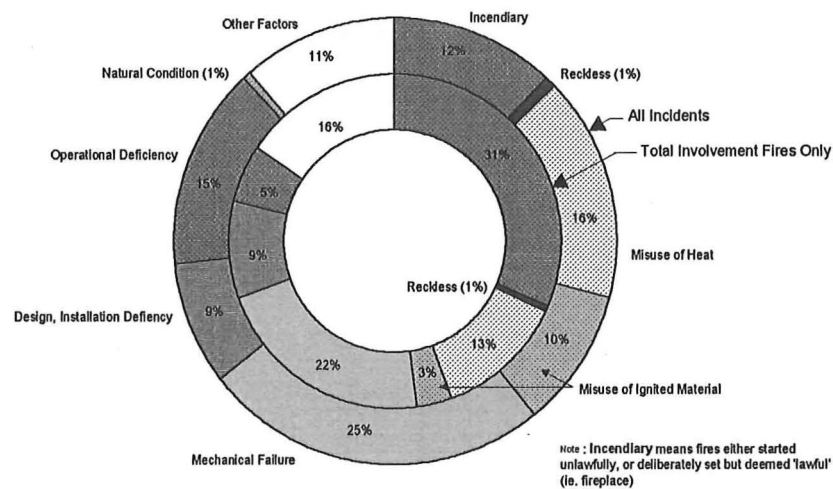


Figure 2.9 : Cause of Ignition in Manufacturing Facilities.

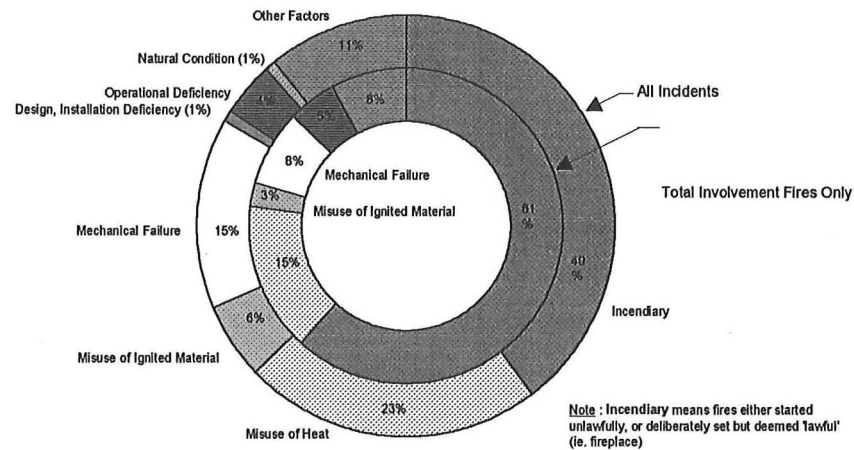


Figure 2.10 : Cause of Ignition in Warehousing Facilities.

## 2.9 Sprinkler Performance

Figure 2.11 records the performance of sprinklers for all the incidents. In most cases no sprinklers are present, and where sprinklers are present it is reassuring to see that there were no cases of sprinklers failing. The areas of concern involve the total involvement fires.

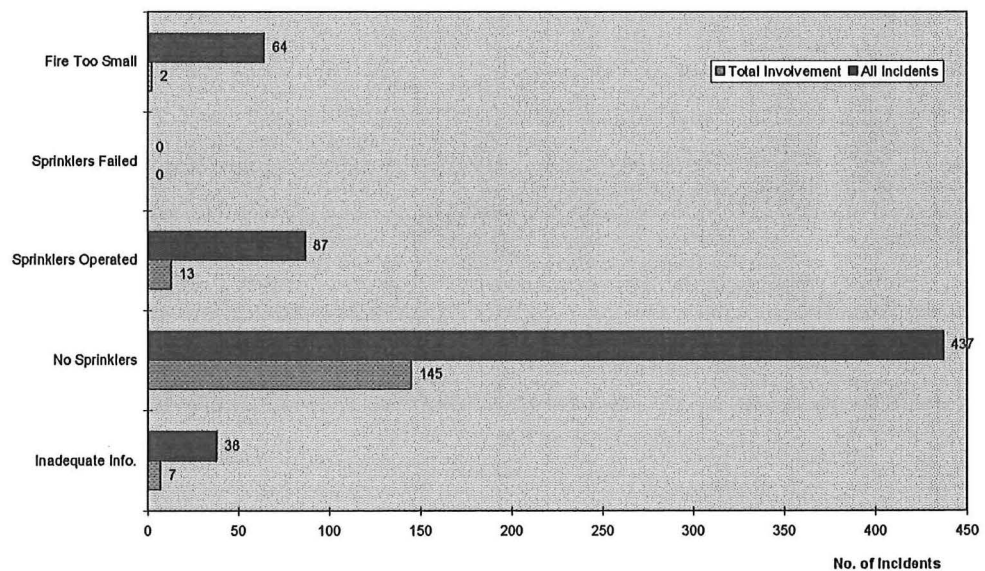


Figure 2.11 : Sprinkler Performance

In two incidents the Fire Service have reported extensive damage, yet the sprinklers did not operate because the 'fire is too small'. In the first case, the damage is caused by flames only; it is assumed that this is therefore an input error, where the flame damage level should have been recorded as 1 (no damage), instead of 7 (complete damage). In the second case the damage is recorded as affecting the

structure and beyond, yet again the sprinklers did not activate due to the fire being too small. Again an input error is assumed to be the problem. These examples are reminders of the margin of error in the received data.

From the results with totally involved fires, there is a record of 13 incidents involving damage throughout the building where sprinklers have activated. This suggests that the sprinklers have been inadequate to control the fires. Ten of these cases have flame damage causing damage throughout the building, with 6 of these cases showing that the flames have caused more damage than smoke or water. This indicates that sprinklers were quite ineffective. The primary purpose of sprinklers is to detect and control a fire while it is still small. There could be a number of reasons as to why some manufacturing and warehouse fires appear to have overcome sprinkler systems. Some are listed below:

1. Incorrect sprinkler installation, including inadequate protection
2. Incorrect storage for the sprinkler hazard classification
3. Failure of sprinkler system (ie. no water, blockage etc.)
4. Incorrect completion of FIRS records
5. Explosion being the cause of fire, either resulting in an excessive number of heads to operate or causing critical damage to the sprinkler system.

Evidence is available in Britain (Ward, 1985) that shows major loss fires resulting from inadequate partial sprinkler protection, and from storing above height limitations. Ward comments that “current levels of protection provide little margin of safety and several factors, such as storage heights being above the recommended values, can easily lead to an expensive fire - even if a large measure of control of the fire by the sprinklers is achieved.’

It is beyond the scope of this study to investigate this issue further, although it does highlight the need to question aspects that are normally taken for granted, such as the reliability of sprinklers, and the control of combustibles in a well designed environment.

## **2.10 FIRS Summary**

The aim of reviewing NZFS statistics on incidents occurring at manufacturing or warehousing facilities, was to identify high and low risk factors. This enables a fire design process for industrial buildings to minimise high risk factors wherever possible.

The FIRS (Fire Incident Reporting System) information received covers incidents throughout New Zealand between 1988 and 1994 that involve:

- manufacturing and warehousing facilities
- floor area greater than 100 m<sup>2</sup>
- call-outs that were not false alarms

Key information that was gained includes:

1. The **occupancy type** with the highest incidence of fires was wood and paper products. This applies to manufacturing (43% of all incidents) and warehousing (19% of all incidents; if general storage is ignored). The relative probability of fires in this group, in comparison to other groups can not be determined due to no other data on total population.
2. Low risk industries include chemical manufacturing, food production (excluding meat processing), and petroleum products. The low level of incidents is attributed to tight industry controls, and the knowledge of the potential outcome of an incident.
3. **Extent of damage** statistics show that in most incidents, damage is either limited to the area of origin, or result in complete damage to the structure. Damage is measured in terms of either flame, smoke or water damage. Those fires limited to the area of origin generally results in minimal smoke and water damage, with mainly flame damage. Fires affecting the complete structure result in damage from smoke, flames and water.
4. In analysing the **month** in which an incident occurs, the results showed three distinct peaks in the number of incidents for all groupings. Again there was found to be no clear pattern for this result, although two of the peak months coincide with the end of financial years.
5. **Time of day** analysis showed that most incidents occur during the day and evening; relatively few incidents occur in the early morning hours (1am-7am). For total involvement fires the predominant alarm time is in the evening (7pm-1am). It is apparent that relatively few industrial complexes are equipped with automatic detection systems - a feature that could reduce property loss, especially when most total involvement fires occur during non-occupied (assumed) periods.
6. The most common **Area of Fire Origin** was found to be in the major use areas: technical or process area for manufacturing facilities, and storage areas for warehouses. The second most common area for manufacturing was service areas.
7. In reviewing the **Cause of Ignition**, it is apparent that incendiary, or an unlawful/suspicious fire, is the major cause. For total involvement fires in warehouses, incendiaries account for 61% of fires. Manufacturing fires show mechanical failure (25%) as the predominant cause for all incidents, but again incendiaries are the leading cause for total involvement fires (31%). This result illustrates that no prediction can be placed on how a manufacturing or warehouse fire will initiate, especially as the nature of an incendiary fire is unpredictable.

8. Automatic alarms, including sprinklers, accounted for 11% of total involvement fires. There were also some events where sprinklers operated but obviously did not control the fire. This indicates that either:

- the sprinkler design is inadequate for the risk
- incorrect storage for the sprinkler classification
- incorrect FIRS record
- failure of sprinkler system (ie. no water, blockage etc.)
- explosion is the cause of fire, either resulting in an excessive number of heads to operate or causing critical damage to the sprinkler system.

## **2.11 Literature Survey**

Two articles are reviewed to support the results from the FIRS survey. They also provide additional information such as probability figures for storage fires, Fire Service response, and cost implications.

### **2.11.1 'The Probability of Fires in Warehouses and Storage Premises'**

This publication (Hymes, Flynn 1992) was carried out by AEA for the Health and Safety Executive (HSE) in Britain. The aim was to determine from statistical data the incidence of fire outbreak in storage premises. Data was obtained from 8 Local Authority districts covering two broad categories:

1. Number of storage premises
2. Number of fires

The difficult area with this study was obtaining accurate figures for the number of storage premises. The main source for this information was the Rating Departments in the Local Authority offices. Due to definition discrepancies the results were compared against information held by:

- The Chartered Institute of Public Finance Accountants
- The Financial Times Business Index
- The Inland Revenue

The resulting data, collected for the period 1976 to 1987, was used to determine the probability of fire outbreak in storage premises using the general equation:

$$p(\text{reportable fire}) = \frac{\text{number of fires}}{\text{number of storage premises}}$$

The two main conclusions were:

1. A warehouse fire is likely to occur in a particular warehouse once every hundred years [ $p(\text{reportable fire}) = 1.2 \times 10^{-2} \text{ year}^{-1}$ ]

2. The probability of a 'serious' warehouse fire occurring in a particular warehouse, is between  $2.5 \times 10^{-3}$  and  $5.5 \times 10^{-3} \text{ year}^{-1}$ .

### ***Serious Fires***

The area of key interest is fires causing extensive damage. In the review of NZFS statistics, these fires were placed under a 'total involvement' category. The AEA report defines a 'serious' fire category, while within the report another study is referred to that uses another definition for 'serious' fire. Clarifying these definitions:

- FIRS Analysis : 'Total Involvement' includes fires that result in either fire, water, or smoke damage to the complete building.
- AEA Report : 'Serious' Fires included all fires where roof collapse occurred. The NZ FIRS do not include this information.
- Baldwin Study (referenced in the AEA Report) : 'Serious' Fires included only those fires that resulted in significant damage to the fabric of the building. This would exclude a number of fires where fire, water or smoke damage occurred throughout, or where the roof collapsed, but did not affect the structure.

The Baldwin study (Hymes, Flynn 1992) concluded that 'serious' fires amounted to around 10% of the total 'reportable' fires giving a  $p(\text{serious fire})$  of  $1 \times 10^{-3} \text{ year}^{-1}$ . This equates to a serious fire every 1000 years, for any given warehouse building. It should be stressed that this data applies to warehouse/storage facilities only, and excludes manufacturing facilities.

### ***General Information***

Other conclusions to come out of the AEA study (Hymes, Flynn 1992) include:

1. The likelihood of warehouse fires was considerably higher than fires or other potential major hazards in the process and manufacturing industry. This is difficult to compare with the NZ results due to the total (population) numbers for the respective groupings being unavailable.
2. The number of serious fires had generally increased over the last 15 years, possibly due to:
  - larger warehouses with less compartments, more pallets, and increased use of combustible wrappings
  - a general increase in the incidence of malicious fires ie. arson, vandalism, fraud etc.

3. Serious warehouse/storage fires not only result in extensive damage to structures and contents, but also present a significant risk to the environment. Warehouses often store large quantities of products that can release toxic fumes and contaminated discharge in a fire situation.
4. The majority of fires (62%) occur between 6pm and 6am, when the premises are presumably unmanned or only a minimal number of staff are present. This correlates with the FIRS information - refer Section 2.5.
5. The main cause of fire outbreak (in order of occurrence):
  - malicious ignition
  - incorrect operation of or faults with electrical appliances and installations
  - careless disposal of smoking materials/matches
6. The warehouse areas with the highest risk for fire outbreak by either accidental or malicious ignition are ramps and loading bays.
7. Alarm systems linked directly to the Fire Service are recommended, to overcome the problem of delayed response.
8. A limited sample of less serious fires (not requiring the turnout of the Fire Service) indicated that between 1 and 5 incidents may occur per storage premises **annually**. This seems quite high, and due to the limited sample is not considered 'valid' without further research.

### 2.11.2 'Some Results from an Analysis of Industrial Fires in Sweden'

The aim of this analysis (Thor, Sedin 1975) was to study the influence of different factors on fire loss, with particular reference to single storey industrial buildings. This work is now over 20 years old, but some of the findings are still considered pertinent to current fire design issues.

#### **Fire Loss**

Based on 69 fires in single storey industrial buildings, the fire loss was divided into the following proportions:

- Building Contents : 51%
- Loss of Profit : 28%
- Building Fabric : 21%

In terms of cost associated with extent of damage, a comparison was made between fires contained to one room, and fires affecting more than one room:

- One Room : 15%
- More Than One Room : 85%



The observation made with the internal fire spread costs, was that partitions in the industrial buildings were often found to be deficient. A recommendation was the improvement of the integrity of fire rated partitions.

### ***Fire Load***

It was concluded that the fire load density was probably the single most important factor for the fire growth and extent of damage. High fire loads were defined as 400 MJ/m<sup>2</sup> total surface area of the fire compartment. Low fire load was defined as less than 50 MJ/m<sup>2</sup>. It should be noted that the New Zealand Building Code places low to medium fire risks below 1000 MJ/m<sup>2</sup>, and medium to high risks at 1000 MJ/m<sup>2</sup> and above.

Low fire load incidents accounted for 42 of the 69 analysed fires. In cases where the building largely consisted of incombustible structures, the spread of fire and amount of loss was generally very small. Low fire load incidents accounted for 60% of the fires, and only 10% of the loss. High fire load incidents however accounted for only 15% of the fires, and 52% of the loss.

### ***Fire Service Response***

In more than 40% of the analysed fires, flashover occurred before the arrival of the Fire Service. The report states that “even at a floor area of only some hundred square meters the total energy released is so large that the amount of water normally available is inadequate to neutralise the energy. Fire Service capacity is then limited to preventing the fire from spreading to adjacent rooms or buildings. There is no possibility to extinguish the burning building until all combustible materials more or less have been consumed.”

Key design deficiencies (besides inadequate partitioning) were the lack of sprinkler protection to control flashover conditions, and roof venting to limit the damage caused by smoke. Inclusion of these features would also allow the Fire Service to suppress the fire, rather than just perform a containment role.

## **2.12 Conclusions**

### **2.12.1 Literature Survey**

A literature survey was completed to assess fire incident trends from other countries. The main conclusions were:

1. High fire load incidents typically accounted for 15% of fires studied, and 50% of the loss.

2. Fire load density is probably the most important factor for the fire growth and extent of damage.
3. The likelihood of warehouse fires was considerably higher than fires in the process and manufacturing industry.
4. A warehouse fire is likely to occur in a particular warehouse once every hundred years [ $p(\text{reportable fire}) = 1.2 \times 10^{-2} \text{ year}^{-1}$ ]
5. The probability of a 'serious' warehouse fire occurring in a particular warehouse, is between  $2.5 \times 10^{-3}$  and  $5.5 \times 10^{-3} \text{ year}^{-1}$ . A serious fire included all fires where roof collapse occurred.
6. Serious warehouse/storage fires not only result in extensive damage to structures and contents, but also present a significant risk to the environment.
7. The majority of fires (62%) occur between 6pm and 6am, when the premises are presumably unmanned or only a minimal number of staff are present.
8. Inclusion of sprinklers and roof vents assists the Fire Service to suppression of the fire, rather than just performing a containment role.

#### **2.12.2 NZFS Incident Records**

A review was carried out on New Zealand Fire Service incident statistics for manufacturing and warehousing facilities, between the years 1988 and 1994. The aim was to identify high and low risk factors associated with recent fires, and recommend improvements to reduce the incidence of serious fires.

The main recommendations from this review (and the literature survey) are:

1. Automatic detection systems should be included in industrial buildings, especially businesses associated with wood and paper products. Sprinkler systems are the preferred option.
2. To minimise unlawful entry, security systems should form part of the fire safety management programme.
3. Periodic risk assessments need to be undertaken to ensure that the correct level of protection and hazard management is occurring to suit the risk and fire safety strategy.

## **3.0 FIRE SAFETY MANAGEMENT**

### **3.1 Objective**

Fire safety management should take place through all phases of a buildings design, use and possible demise. The objective of this section is to highlight appropriate fire safety management techniques, and reinforce the need for fire safety to be continually reviewed and reinforced.

The fundamental concept with fire safety management is loss control, or to minimise both the chance and consequences of a serious fire. Loss control is not only an important consideration during a buildings design phase, but also once the business is operational. An on-going programme should be introduced that incorporates:

1. Fire prevention training and audits.
2. Evacuation systems.
3. Pre-incident plans.

This programme aims to ensure:

- Fire protection systems can still meet hazard demands.
- Personnel understand fire safety and know how to react during a fire incident.
- Maintenance programmes keep fire protection equipment fully functional, escape systems operating as designed, and process equipment from becoming possible sources of ignition.
- In the event of an emergency responding fire service personnel have the best opportunity to attack the fire and minimise damage and disruption.
- Contingency plans are in place for post-fire business continuity.

The following sections discuss the on-going fire safety management programme in detail. Fire design methods for single storey industrial buildings are provided in Part 2.

### **3.2 Loss Control**

Warehouses and manufacturing buildings present significant fire loss potential. Statistics from NFPA 1420 [1993] show that in the USA over the period 1982-1986, fires in warehouses totalled 14.2% of all reported fires but equated to 38.3% of the total cost of fire losses. Some of the contributing reasons for this result are:

- large, open compartments.
- high combustible loading, through high rack storage and the use of high hazard materials such as plastics, flammable liquids and wood products.
- inadequate fire protection systems.

Davis & Moore [1991] concluded that the only proven method of controlling a warehouse fire is with a properly designed and maintained automatic sprinkler system. Other features that should be carefully considered during the design phase are smoke management systems, fire separations, site security and a loss control strategy.

Developing a loss control strategy firstly requires determination of the acceptable loss for a given premises, where loss can be measured in terms of property, life, environment, and/or business continuity. For issues such as life protection and to a lesser extent, environmental protection, legislation establishes a minimum standard of fire safety [NZ Government, 1991; BIA, 1992].

For issues such as property protection and business continuity, an owner needs to establish an acceptable level of risk for the operation. As discussed by Keey [1987] this decision often narrows to a cost versus benefit question. Budgets are usually expected to control the extent of fire safety features, remembering there can be a point where extra investment into a facility will not provide the equivalent level of benefits.

Proposed legislation in Britain will introduce the need for fire risk assessments to be carried out in some buildings, as well as the preparation of written emergency plans [LPC, 1995]. Only the latter currently occurs in New Zealand, where the introduction of a risk assessment design procedure is seen as an improvement for design options. This approach is already being developed in Australia and Canada as a workable fire engineering design tool [BRRTF, 1991].

### **3.3 Fire Prevention**

Fire prevention relies on effective and regular training and audits. The success of a fire prevention programme depends on the cooperation of site personnel, which in turn relies on their awareness and reaction to hazardous situations. Training and audits need to be regular to avoid complacency plus maintain reaction skills.

Training courses should be held at least once a year, and cover the use of fire fighting equipment, evacuation procedures, and basic responsibilities for preventing or controlling fires. Company policies on hot work, smoking, use of machinery, security, and general housekeeping need to be reinforced.

Audits should be undertaken by independent, qualified persons to cover the following areas:

- capability of fire protection equipment for the current hazards. Rearranging of stored goods may result in the sprinkler system being under-designed, or new processes may require additional hand held fire fighting equipment.
- maintenance of fire protection equipment, including integrity of fire separations, and operation of smoke management systems.
- identification of potential ignition sources, such as heaters, unsafe use of electricity, or handling of solvent rags.
- identification of hazardous goods or operations that could be better controlled. This could pertain to handling of flammable paints, storage of combustible goods or use of process machinery.
- general housekeeping, including management of rubbish, smoking, security, and material handling.

Owners of industrial buildings need to develop a culture that accepts fire prevention training and audits as part of the business plan. Design documents should include this recommendation alongside prescribed maintenance requirements.

### **3.4 Evacuation Systems**

An important component in a loss control strategy is life safety. A successful life safety system ensures that building occupants either escape, are rescued or find a place of refuge before untenable conditions occur. The design of an appropriate life safety system is discussed further in Section 6.

For an existing building there is a need to establish and maintain an approved evacuation system. This does not only involve the evacuation procedure as required under the Fire Safety and Evacuation of Buildings Regulations (1991), but also:

- meeting all annual Building Warrant of Fitness requirements, in accordance with the NZ Building Act. This includes ensuring all fire protection equipment is properly maintained, all means of escape are freely accessible, and combustible risk controlled.

- ensuring there is an adequate means of alerting occupants, exit routes are clearly marked, a control board is located near the alarm panel, and there is a muster point.
- appointment of building wardens to supervise evacuation, and ensure all occupants are safe.
- conducting trial evacuations on a 6-monthly basis.
- establishing a contingency plan to minimise disruption to the operation of the business in an emergency, including security of records, alternate storage facilities and adequate insurance provisions.

### **3.5 Pre-Incident Planning**

Unlike fire prevention inspections, pre-incident planning assumes an incident will occur. It makes no special effort to prevent a fire or eliminate a hazard, but rather to prepare for an incident, regardless of likelihood [NFPA 1420, 1993].

The primary purpose of a pre-incident plan is to ensure that responding personnel can effectively manage emergency incidents with the available resources. Pre-incident plans minimise the time fire fighters need for confirming the site fire protection capabilities, the hazards and the available site support services.

The information required for a pre-incident plan can be placed in 5 categories:

- Building details, including construction, contents and occupancy. This should be supported by plans and other records.
- Fire protection features, including water supply sources.
- Environmental factors.
- Area knowledge, including neighbouring occupancies, town water supplies, and access.
- Site support personnel.

A pre-fire planning session with site and Fire Service personnel is essential in the formulation process. Emergency drills should be carried out periodically to test the plan, and this should include consultation with the Fire Service to ensure changing site conditions have not affected details in the plan [Plaughter & Burns, 1991]. Changing site conditions is particularly relevant to sprinkler systems, where they are usually designed to meet a minimum standard and any change in conditions could leave the system inadequate for the new conditions.

Other operating features that are variable include:

- storage quantity and layout, including storage heights.
- commodities in use, with respect to combustibility and toxicity.
- material handling practises.
- plant layout and use.

Personnel features that are liable to change include the number of occupants, their activities, and familiarity and training with regard to the building operations and fire protection features and practices [NFPA 1420, 1993]. Again these details should be periodically re-evaluated and the pre-incident plan changed accordingly.

Figure 3.1 shows a typical pre-incident site data sheet for an industrial location, and figure 3.2 provides an example of this data sheet in use.

### **3.6 Conclusions**

#### ***Design Process***

1. Loss control should be reinforced during the design process. This requires determination of acceptable loss, and application of risk assessment and cost/benefit techniques.
2. Current regulatory requirements do not address property and business loss control (for the owner); only life safety, spread of fire, and environmental protection issues.

#### ***Existing Operation***

3. An on-going fire safety management programme should be introduced that incorporates:
  - Fire prevention training and audits.
  - Evacuation systems.
  - Pre-incident plans.
4. Pre-incident planning should be encouraged to ensure that responding personnel can effectively manage incidents with available resources.
5. Contingency plans need to be in place to minimise disruption to the operation of the business in an emergency.

Figure 3.1 : **PRE-INCIDENT SITE DATA SHEET**

Date : .....

**SECTION A : Company Details :**

Company Name : .....

Premises Name : .....

Contact Person &amp; Ph. No. : .....

Location : .....

Description of Operations : .....

No. of Employees : .....

**SECTION B : Protection Systems**

Description of Systems : .....

In-rack Sprinklers Provided : ☐ Yes ☐ No

Sprinkler Design : ..... lpm ..... kPa

Fire Pump : ..... lpm ..... kPa

Site Reservoir : ..... l capacity

Venting : Natural Vents : ☐ Yes ☐ NoAutomatic Vents : ☐ Yes ☐ No

Control Panel Location : .....

System Description : .....

Alarm Panel Location : .....

Fire Service Connection : ☐ Yes ☐ No**SECTION C : Fire Service Response**

Site Access : .....

Door Locations / Forcible Entry Notes : .....

.....



Towns Main : Flow ..... lpm ..... RP ..... SP

Hose Stream Supply : On Site : .....

Public : .....

#### **SECTION D : Construction Details**

Storage Configuration and Hazards : .....

Critical Exposures : Side 1 ..... Side 2 .....

Side 3 ..... Side 4 .....

Dimensions : Width ..... Depth ..... Height .....

Wall Construction : .....

Support Structure : .....

Roof Construction : .....

Fire Walls and Doors : .....

#### **SECTION E : General Details**

Assembly Points : .....

Building Warden : Day ..... After Hrs .....

Site Services & Shut Off : .....

.....

#### **SECTION F : Block Sketch :**

Figure 3.2 : **PRE-INCIDENT SITE DATA SHEET** (Example)Date : 16.7.95**SECTION A : Company Details :**Company Name : Lotsa Plastic Bottles Ltd.Premises Name : The Brown BottleContact Person & Ph. No. : Mr P.S. Hedd - Manager ; 3666.888Location : 38 Sir Rhosis Ave., SydenhamDescription of Operations : Storage of PVC BottlesNo. of Employees : 16**SECTION B : Protection Systems**Description of Systems : Smoke detection & manual call points, linked to sounders and the Fire ServiceIn-rack Sprinklers Provided : ☐ Yes ☒ NoSprinkler Design : N/A lpm kPaFire Pump : N/A lpm kPaSite Reservoir : N/A l capacityVenting : Natural Vents : ☒ Yes ☐ NoAutomatic Vents : ☐ Yes ☒ NoControl Panel Location : NoneSystem Description : 6 off natural roof vents operated by fusible linksAlarm Panel Location : Adjacent to OfficeFire Service Connection : ☒ Yes ☐ No**SECTION C : Fire Service Response**Site Access : 2 entrances off Sir Rhosis Ave.Door Locations / Forcible Entry Notes : 4 doors into warehouse, site gates locked after hours, keys held by Fire Service

Towns Main : Flow 2000 lpm 225 RP 420 SP

Hose Stream Supply : On Site : Fire hydrant by south gate

Public : Hydrant on 150 mm main, 50 m north of site

#### SECTION D : Construction Details

Storage Configuration and Hazards : PVC bottles stacked 5 m high. Racks = 8 m x 1.6 m  
4 m separation between racks; no. of racks = 16

Critical Exposures : Side 1 10 m to road Side 2 10 m to clothing manuf.

Side 3 1 m to timber yard Side 4 10 m to eng. workshop

Dimensions : Width 50 m Depth 24 m Height 8 m to top of roof

Wall Construction : Concrete tilt panel on 3 sides, steel sheeting on road side

Support Structure : Steel portal frame, concrete cover on east boundary columns.

Roof Construction : Steel long-run roofing with skylight translucent panels

Fire Walls and Doors : None

#### SECTION E : General Details

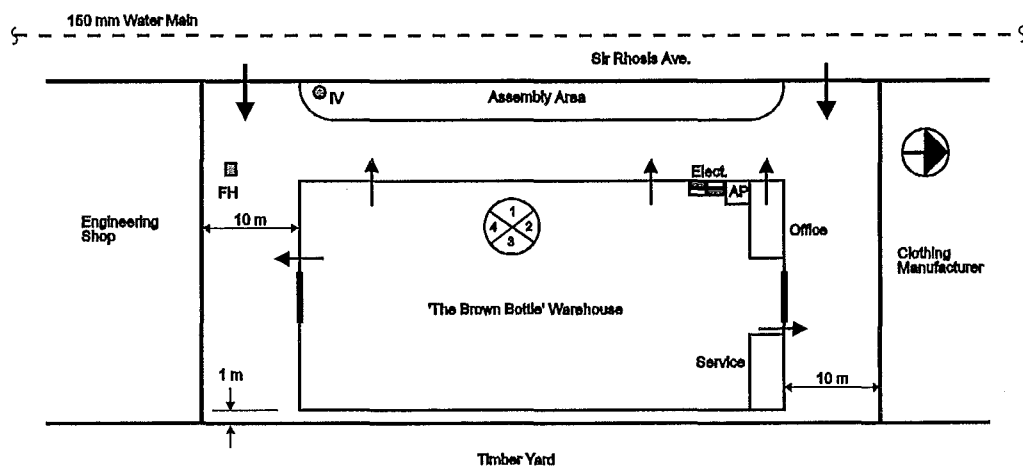
Assembly Points : Front of building on grass area

Building Warden : Day Iva Dubull After Hrs Mr P.S. Hedd

Site Services & Shut Off : Intruder control in warehouse - contact Armourguard.

Site power : 400V, 150A - S/B by Office. Isolating valve for stormwater by south gate.

#### SECTION F : Block Sketch :



## **4.0 ENVIRONMENTAL PROTECTION**

### **4.1 *Environmental Effect of Fires***

The design of industrial buildings should not only consider the effects of fire within the immediate site area, but also the possible effects to the greater environment.

In a fire situation the introduction of high temperatures and large quantities of water can result in chemical cocktails that freely disperse to the environment, causing toxic or acid air emissions plus ground and surface water contamination. Serious damage can result to the ecosystem and seriously affect life forms ranging from terrestrial flora to native animals.

The local concentration of air pollutants in smoke is usually reduced significantly due to dilution and distribution, and in most cases there is only minor danger of people being directly poisoned [Miles et al 1994]. The principal environmental concern is either soil or water contamination.

The major focus at a fireground involving toxic substances is therefore containment of solid and liquid waste, and proper handling of plant residue. The first priority after controlling the fire, is to retain any polluted run-off water before soil seepage or leakage into sewer systems can occur. Once collected, the contaminated waste must be correctly disposed of within an approved hazardous waste dump and the site thoroughly cleaned.

### **4.2 *Case History***

The following environmental incidents were all due to fire. It is important to note that other major environmental incidents at industrial plants have occurred due to non-fire related causes. The usual cause is release of toxic vapours as occurred at Bhopal, India, or Seveso, Italy [Keey 1987].

#### **4.2.1 Chemical Fire, Mount Wellington, NZ (1984) [Keey 1987]**

At approximately 5pm, Friday 21 December 1984, a series of explosions occurred at one of the chemical warehouses of I.C.I. New Zealand Ltd. in the Mount Wellington suburb of Auckland. The resulting fire engulfed the warehouse, which housed a variety of pesticides, herbicides, health-care products and swimming pool chemicals.

The emergency response involved 86 firemen and 18 appliances. Houses and businesses within a 1km radius were evacuated. The fire was contained after 4 hours, but resulted in 50 tonnes of chemicals being burnt, and 5 to 10 tonnes being diluted by fire fighting water and discharged into the local estuary via stormwater drains.

The Health Department arranged tests of soil and debris, to monitor the effects of chlorine and dioxin released products. Thirty four firefighters needed hospital treatment for rashes from contamination. Eight were still in hospital a fortnight later, and a small number of firefighters had continuing skin problems six months after the fire. The long term effects to both firefighters and the environment appeared to be minimal.

#### **4.2.2 Vapour-Cloud Explosion, Flixborough (1974) [Keey 1987]**

A massive explosion occurred on a Saturday afternoon in June 1974, at the Flixborough works of Nypro (UK). The force of the explosion was estimated to be equivalent to between 15 and 45 tonnes of TNT. On site, 28 people were killed and 36 injured; off-site injuries and damage was widespread, but no-one was killed.

The cause of the explosion was the rapid escape of cyclohexane under pressure and at a temperature of 155°C. Key concerns to come out of the resulting inquiry were inadequate quality management, and the excessive storage of cyclohexane on the site.

#### **4.2.3 Chemical Warehouse Fire, Allied Colloids Plant, Bradford (1992) [Philip 1995]**

A fire broke out in an oxidising store within a raw materials warehouse in the afternoon of 21 July 1992, at the Allied Colloids Plant, Bradford, U.K.. The warehouse contained almost 1000 tonnes of 225 different packaged substances. The resulting fire spread to drums stored outside and containers immediately adjacent to the warehouse. Eighteen million litres of water were used in controlling the fire.

By the end of the afternoon the warehouse had been completely destroyed and polluted fire fighting water was causing damage to the local river system. Fallout from the smoke plume was reported and confirmed up to four miles away. The entire workforce had been evacuated along with a small number of local residents.

Once the containment tanks at the sewage works became full, the run-off water had to be released into the river system. This resulted in fish kills as far downstream as 30 miles. About 20,000 fish are thought to have been killed over a period of several days, probably by deoxygenation of the water. Fortunately the biological regenerative capacity of the rivers remained intact and the system was able to return to a balanced existence.

The major environmental impact was this release of water run-off into the waterways. The effects of the smoke were minimal, although local residents were advised to not eat garden produce until two months after the event.

#### **4.2.4 Chemical Warehouse Fire, Schweizerhalle (1986) [Hölemann]**

On the 1st November 1986 a fire burnt down a warehouse for chemicals in Schweizerhalle near the city of Basel, Switzerland. A major environmental incident resulted from the chemicals mixing with the extinguishing water and discharging into the Rhine River. Approximately 20 million litres of water mixed with pesticides and a toxic water soluble mercury compound.

In the upper reaches of the Rhine, all eels and many micro-organisms died, and water-works that took their water from the Rhine had to temporarily cease withdrawal. This incident set back an otherwise successful programme of controlling pollutants into the Rhine and its tributaries, and recovering the waterways.

#### **4.2.5 Summary**

Problems highlighted with these chemical warehouse fires include [Prosser 1991]:

- Building Design - no internal compartmentation. This not only creates a substantial fire load, but also allows spilled chemicals to mix.
- Pollution Control - no bund walls, interceptors or water run-off catchment basins.
- Fire Protection - no automatic suppression or detection systems.
- Emergency Procedure - inadequate information available for the responding emergency services, including the absence of a company chemicals adviser (Schweizerhalle fire).
- Fire Fighting Tactics - uncontrolled application of water, and inadequate attempts to contain water run-off.

### **4.3 *Mandatory Requirements***

#### **4.3.1 Legislation**

##### ***Resource Management Act***

The New Zealand Resource Management Act 1991, requires any development proposals to assess the effect that the development would have on the environment [NZ Government 1991]. Section 3 of the Act defines the meaning of 'effect' and includes "any potential effect of low probability which has a high potential impact". This can involve a wide range of possible events, such as radioactive or toxic release due to a process accident, or the discharge of contaminants into waterways and the air as a result of fire.

The N.Z. Resource Management Act (Section 341) does provide the means to defend an offence, on the grounds that the particular event was beyond the control of the defendant, and:

- The event could not reasonably have been foreseen or been provided against; and
- The effects of the event were adequately mitigated or remedied by the defendant after it occurred.

This implies that the owner of an industrial plant, where a fire resulted in significant pollution to neighbouring waterways, could defend prosecution under the Act by arguing that the event could not be foreseen. In fact, the purpose of this section is to highlight the due care required by owners - particularly those involved in the use of hazardous substances - to ensure all possible effects on the environment are considered so as to either eliminate, isolate or control the risk. If the owner can not prove that due care was carried out to minimise the effect of an event, then a prosecution is possible.

This is reinforced by the Fourth Schedule in the Act, dealing with assessment of effects on the environment. One area listed for particular consideration is the risk to the environment through natural hazards or the use of hazardous substances or hazardous installations.

### ***Building Act 1991***

The Building Act 1991 also places a responsibility on a building owner to protect the environment from any event originating within a building operation. The Regulations to the Act: also known as the N.Z. Building Code [BIA, 1991], states in Clause F1: Hazardous Agents on Site that an objective is to 'safeguard people from injury or illness caused by hazardous agents or contaminants on a site'. Clause C3: Spread of Fire states that an objective is to 'safeguard the environment from the adverse effects of fire'.

Clause C3 also includes functional and performance requirements pertaining to the environment:

- [Functional Requirement - C3.2] 'Buildings shall be provided with safeguards against fire spread so that . . . significant quantities of hazardous substances are not released to the environment during fire.'
- [Performance Requirement - C3.3.10] 'Environmental protection systems shall ensure a low probability of hazardous substances being released to:
  - a) Soils, vegetation or natural waters
  - b) The atmosphere, and
  - c) Sewers or public drains.

This applies only to *buildings* where significant quantities of *hazardous* substances are stored or processed.'

Most industrial operations store and use hazardous substances. A moot point is when does this quantity becomes 'significant' (this term is not defined).

The definition for hazardous substance is given in the Fire Service Act [NZ Government, 1975]:

"*Hazardous substance* means:

- a) Any dangerous good (as defined by the Dangerous Goods Act 1974); and
- b) Any toxic substances (as defined by the Toxic Substances Act 1979); and
- c) Any other flammable, toxic, explosive, infectious, radioactive, or other substance that may impair human, animal, or plant health."

#### **4.3.2 Acceptable Solutions**

The N.Z. Building Code does not currently provide an acceptable solution to achieve the performance requirement stated in clause C3.3.10. For major processing plants, and hazardous stores, a detailed investigation including risk assessment should be carried out as described in section 4.4.

For simple industrial buildings storing or processing significant quantities of hazardous materials, the Territorial Authority is required to ensure that the performance requirement is met.

In most cases this can simply be achieved by:

- a) Installing an automatic sprinkler system, and/or
- b) Providing bunding to contain spillage's and fire fighting water

In summary, it is considered that the NZ Building Act and Code give insufficient guidance and emphasis to the control of environmental damage.

#### **4.4 Industrial Plant Design**

The requirement to safeguard the environment from fires' adverse effects is now part of New Zealand legislation, and is in line with design procedures in European countries. The most appropriate time to establish management systems to overcome potential environmental effects is during the plant design period.



#### 4.4.1 Risk Assessment

An important part of the design process is consideration of the use and effects of hazardous substances. The first step is identifying the risk, and planning effective controls [Chivers 1988]. This involves:

- establishing the intended industrial process.
- assessing the risk (HAZOP studies).
- locating plant sites to suit the risk.
- ensuring effective safety features are incorporated.
- establishing effective company safety policies, including inspection procedures, emergency procedures, and an incident reporting and review system.

A risk assessment should determine the appropriate level of fire protection and process control. Factors such as the method of containment, quantity of dangerous goods, type of dangerous goods, and expected effect on the environment, all combine to establish the hazard category [Hölemann 1994]. The method of active fire protection, and level of emergency plan, is designed to suit. Risk assessment computer models are currently being developed to assist in this process [McQuaid 1992].

A typical risk assessment approach is [Hodge 1995]:

1. Identification of the hazards
2. Assessment of the possible extent of damage and the probability of occurrence.
3. Formulation of protection objectives.
4. Selection of an appropriate protection plan and appraisal of the degree of safety.

This exercise will then determine the appropriate level of fire protection:

1. Structural - small fire compartments only.
2. Surveillance - fire compartments and automatic detection systems.
3. Surveillance plus permanent company fire brigade.
4. Extinguishing system.
5. Extinguishing system plus permanent fire brigade.

and also determine necessary construction features to eliminate, control or minimise environmental effects.

#### 4.4.2 Plant Design

In the advent of a fire the ideal outcome is to contain or extinguish the fire before any pollution occurs. This is extremely difficult to guarantee although systems can be put in place that approach this ideal. An automatic extinguishing system such as sprinkler protection can effectively control a fire once it has reached a detectable level. The development of Early Suppression Fast Response systems improve on this position by provide a probable suppression outcome [Allard, 1994].

Plant design can include features such as sprinkler protection and a waste water containment system to minimise the effect to the environment and to the business operation.

Areas that should be considered with the overall plant design are [Chivers 1988]:

- minimal storage and use of hazardous goods on site.
- adequate storing and containment of hazardous goods, including the separation of compounds that will result in adverse reactions if mixed.
- safety devices to complement fail-safe procedures, and to monitor temperature and pressure conditions.
- fire protection and detection devices, including communication systems to emergency services.
- emergency containment and separation facilities.
- emergency and contingency plans, vetted by relevant emergency services. This includes environmental monitoring facilities available during an emergency, and a plan to cope with the aftermath.
- familiarisation exercises by emergency personnel, including site staff.

#### 4.4.3 Containment

A clear responsibility is to contain any polluted liquid waste to the affected site. The simplest methods to achieve this are by either bunding around hazardous areas or providing containment reservoirs.

Bunding should take the form of an impervious raised area around a plant item such as an oil tank. The height of the bund would provide sufficient volume to contain all of the contents of the plant item plus the quantity of fire fighting medium expected to be applied, as agreed by the Fire Service. For transformers protected by sprinklers this is equivalent to 20 minutes sprinkler operation. The bund should also have outlets at the lowest points to allow removal of the waste to waste cartage operators.

Containment reservoirs are usually underground to take advantage of gravity feed. They can act as intermediary separation tanks for normal stormwater purposes, but include main shutoff valves to ensure isolation during an emergency. As with the bunding systems, they have to be sized to cope with worst scenarios, and include drainage facilities for transfer of the contaminated product.

The capacity of these systems increases markedly if no sprinklers are installed over the risk areas. Control of a fire is then reliant on manual fire fighting and can involve around five times the quantity of water [Peet, 1993].

#### **4.4.4 Emergency Plan**

The emergency plan and supporting communication system are very important in minimising damage to both property and the environment. If there is a risk of environmental contamination, then water, drainage and health authorities need to become involved at a very early stage. This is in accord with the Resource Management Act expecting effective action by the company after an 'offending' event has occurred.

Provision should be made for rapid air and ground analysis to take place during an incident if possible. Otherwise plume toxicity information should be established to help predict the possible environmental effects. An emergency plan should also consider the after-effects in terms of coping with the media, residents, business commitments and restoration of the environment.

Exercises should be conducted regularly, including trial incidents, and visits by outside authorities. External reviews should also be undertaken on a regular basis, to ensure a minimum safety standard is maintained.

There is a clear responsibility by all parties involved in minimising pollution during an industrial spillage, leakage or fire,. This includes regulatory authorities and emergency personnel, but most of all the business owners.

#### **4.5 Conclusions**

1. The Resource Management Act places an expectation on owners of industrial plant to exercise due care in the design, construction, maintenance and operation of the plant, to ensure the development does not have an adverse effect on the environment. The owner is therefore expected to either eliminate, isolate or control all environmental risks including those resulting from fire.
2. The Building Act regulations state as an objective that the environment is to be safeguarded from the effects of fire. How this is to be achieved is not addressed in the Acceptable Solutions to the regulations.

3. There is a clear need to provide acceptance criteria for hazardous processes and their containment under fire conditions to safeguard the environment.
4. Plant design for sites containing 'significant' hazardous substances should include risk assessment and result in safety controls to suit the risk.
5. The ideal solution is to control or extinguish the fire before any pollution occurs. Automatic extinguishment systems such as sprinklers protection can assist in minimising both air and water pollution.
6. Bunding or containment reservoirs are an important environmental safety feature for sites with hazardous goods. The sizing is dependant on the quantity of goods held and the volume of fire fighting water expected to be applied.
7. Auditing, trial emergency procedures, and familiarisation by outside authorities need to become part of the industry culture. The scale of an industrial fire is often underestimated.

# **FIRE DESIGN OF SINGLE STOREY INDUSTRIAL BUILDINGS**

## **PART 2 : FIRE SAFETY DESIGN**

### **CONTENTS:**

- 5.0      Fire Design Procedure**
- 6.0      Life Safety**
- 7.0      Detection and Sprinkler Systems**
- 8.0      Roof Venting**
- 9.0      Structural Performance**
- 10.0     Fire Service Intervention**
- 11.0     Fire Fighting Design**
- 12.0     Conclusions and Recommendations**

## 5.0 FIRE DESIGN PROCEDURE

Fire safety design involves a wide range of design features such as means of escape, fire resistant construction, and fire fighting facilities. The design process becomes complicated when buildings containing high risk combustibles, such as single storey industrial buildings, are involved. This usually requires specific fire engineering design where potential fire scenarios need to be modelled to determine the minimum fire protection necessary.

### 5.1 *Objective*

The aim of this section is to provide a suitable fire design procedure for a fire within a single storey industrial building. Suitable protection strategies to achieve the minimum required fire safety levels (based on the design fire) are discussed in following sections. These include automatic suppression and detection systems, roof venting, and building construction.

The intent of developing a fire design procedure is to assist in the following

1. Prediction of the likely outcome of a fire, based on fuel description and building layout.
2. Determination of the risk of fire spread to neighbouring property.
3. Assessment of the benefits of enhanced active and passive fire protection to minimise the identified risks.

### 5.2 *Fire Development*

A typical graph for a simplified fire development sequence is shown in Figure 5.1. This shows the main stages of fire development in an unprotected single storey industrial building:

- fire growth; this can continue until a flashover condition occurs, or until the maximum fuel surface is burning.
- steady state condition; this can be ventilation or fuel controlled depending on whether the burning rate of the involved fuel is greater or less than the relative burning rate possible due to available ventilation openings. The melting of skylights and roof collapse increases the available ventilation and can alter the heat release rate (ie. allow more fuel to burn).

- fire decay; the decrease in heat release rate occurs once the available fuel surface area decreases due to depletion, or smothering.

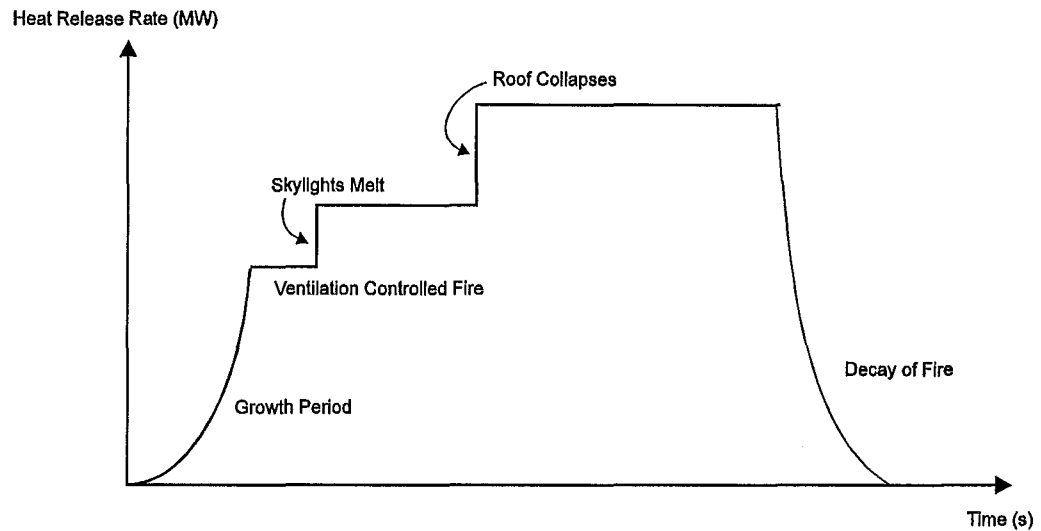


Figure 5.1 : Typical Fire Development Profile for Single Storey Building

### **Typical Fire Scenarios**

Figures 5.2 to 5.4 show the fire development process as time snapshots based on three scenarios. These diagrams compare the expected outcome of a fire in an industrial building based on different protection systems. Reference is also made to life safety:

Fig. 5.2: No Automatic Protection Systems - the design fire is able to develop and spread without any restrictions, until the possible melting of translucent roof panels. Occupants are not aware of the fire until someone notices smoke or flames, and raises the alarm. This delayed response can result in insufficient time being available for successful escape before untenable conditions occur. The fire is likely to flashover and cause total destruction of the building and contents.

Fig. 5.3: Smoke Venting System - the design fire is expected to develop until an automatic detector senses the fire and initiates the roof ventilators. These can be in the form of fan assisted or natural ventilators, and they should be designed to extract enough smoke to keep the upper smoke layer above the occupants and combustible product for a minimum time period. This time period may be based on the expected escape times or Fire Service response times. The fire is still expected to spread throughout the building if there is no fire fighting water applied.

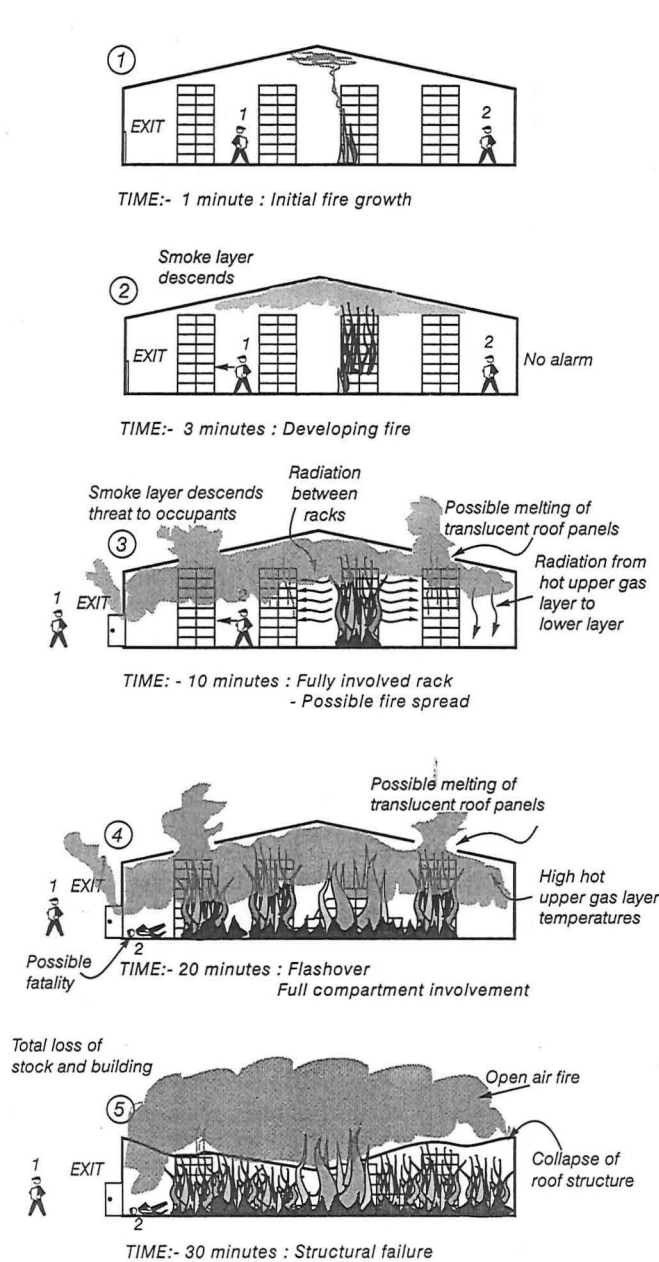


Figure 5.2 Fire development with no protection system

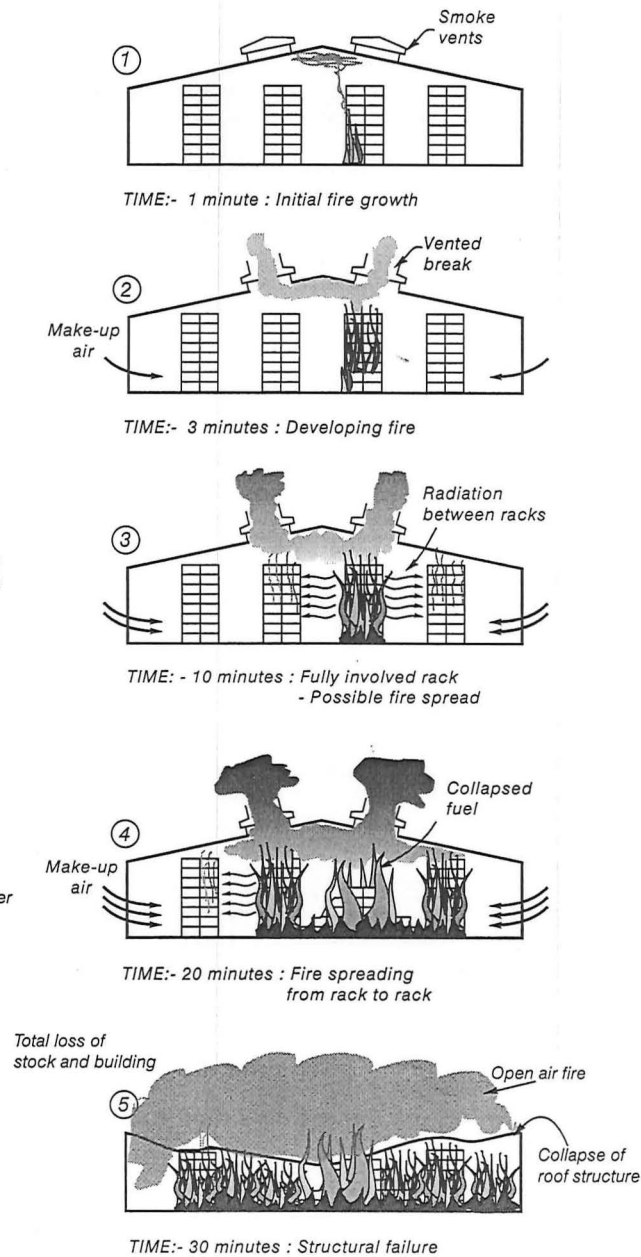


Figure 5.3 Fire development with automatic roof vents

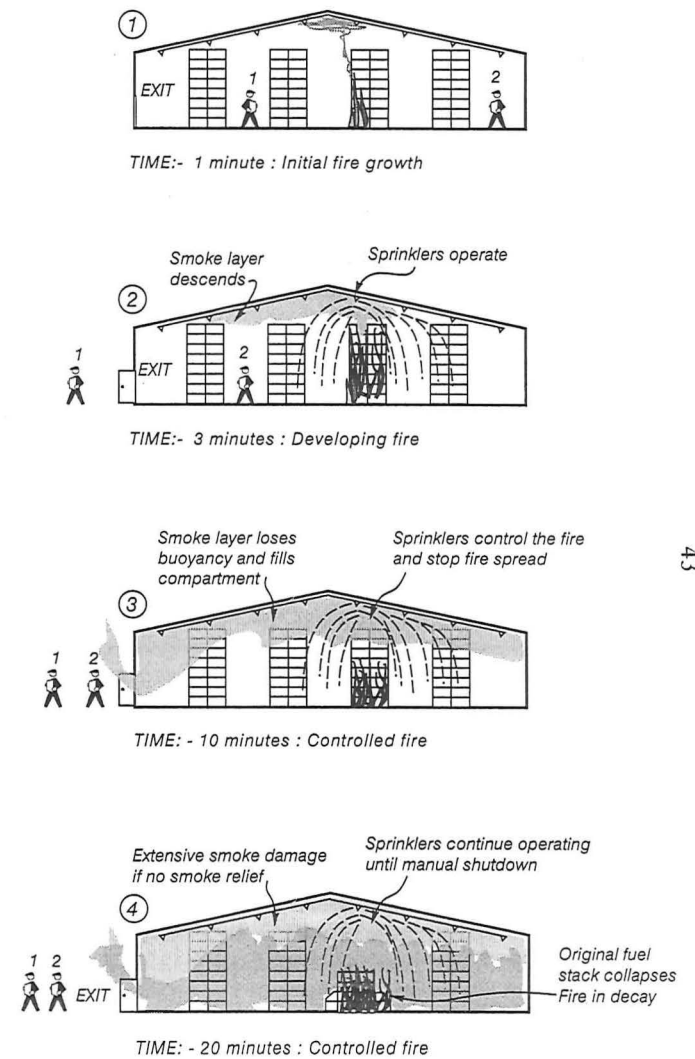


Figure 5.4 Fire development with sprinkler system



Fig. 5.4: Sprinkler Activation - this is the only effective means of controlling a typical industrial fire. The activation of the sprinklers also provides a means of alerting the occupants and the Fire Service. Smoke from the fire is expected to continue to form below the ceiling and then lose buoyancy as a result of the sprinkler action. Unless there is effective smoke venting, extensive smoke damage is expected to occur, but otherwise the building and stock are left relatively undamaged.

### 5.3 Fire Design Procedure

Figure 5.5 shows the *fire development process*, from fire initiation to full involvement for a fire within an industrial complex. A parallel time line highlights the expected response times of detection equipment and the Fire Service, although the effect of these events is not reflected in the flow chart. Other factors that could affect the fire development such as fire barriers or sprinkler systems are also ignored. The intent is to present the effect of a full involvement fire without any restrictions. This is seen to be the worst case scenario.

A *fire design procedure* should identify the variables that can affect the outcome of a fire, ranging from fuel layout to Fire Service response. A general procedure is represented in a series of flow charts (Figures 5.6, 5.9 and 5.10). There are some conditional events as well as alternative outcomes, with the procedure following the main stages of fire development:

- Fire growth
- Fire spread within the firecell
- Open air burning following roof collapse
- Boundary exposure

The use of computer models and equations to predict fire behaviour in large compartments is considered to be crude, largely due to these relationships being based on correlations applicable to small compartments. The results however tend to be conservative with fire spread assumed to occur easily, minimal heat loss expected out of the compartment, and the steady state condition being unimpeded by changing fuel profiles.

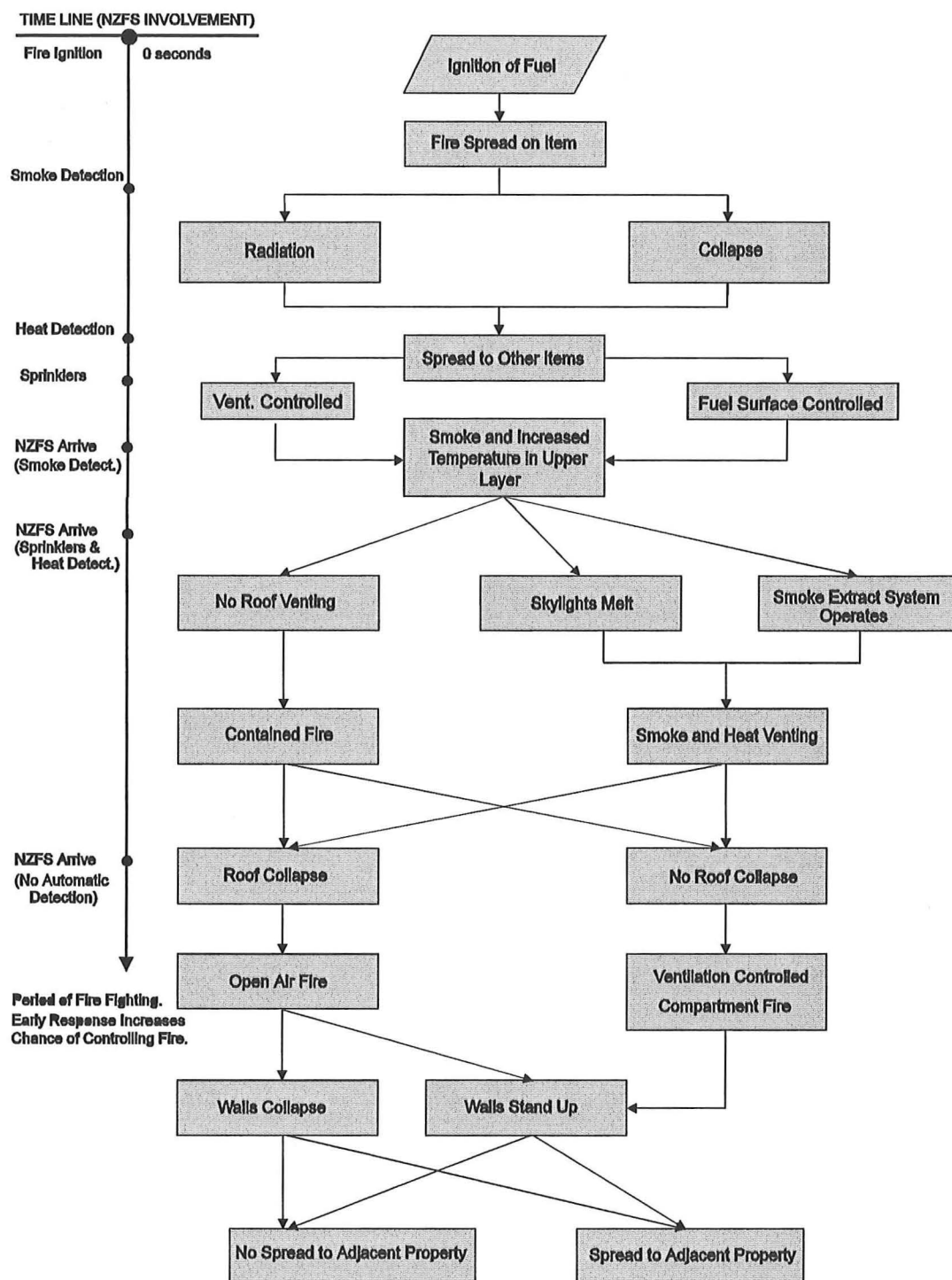


Fig. 5.5 : Fire Development : Single Storey Industrial Buildings

## 5.4 Fire Growth

Figure 5.6 represents the growth and steady state phases of fire development to a point where the fire spreads to external exposures. For fire growth, a recommended design procedure is:

1. Establish a schedule of the products within the compartment:

Ref.	Description	Quantity (kg)	Surface Area (m <sup>2</sup> )	Calorific Value (MJ/kg)	Fire Load Energy Level (MJ)	Burn Rate (g/s.m <sup>2</sup> )	Peak Heat Release Rate (MW/m <sup>2</sup> )	Growth Rate

Note the following publications can be referred to for material data:

- NFPA 92B (peak HRR, growth rates) [NFPA, 1991]
  - SFPE Handbook (calorific values, burn rates) [Tewarson, 1992; Babrauskas, 1992]
  - Fire Engineering Design Guide (FLED's, burn rates) [Buchanan, 1994]
  - Fire Dynamics, D. Drysdale (burn rates) [1985]
2. Determine the Fire Load Energy Density (FLED - MJ/m<sup>2</sup>) for the compartment floor area and compare to averaged values for the general use. Review the schedule if these values differ markedly.
  3. Provide a floor plan showing the layout of the fuel, including separation distances and cross reference to the initial schedule.
  4. Use FPETOOL "Formula" to establish a fire growth profile for each fuel item. Simulate the fire growth rate for the fuel by applying the "t-squared" approximation. References such as NFPA 92B [1991] lists various fuel items in terms of slow, medium, fast or ultra-fast fires, where these classifications are based on the time required for a fire to grow to a rate of heat release equal to 1.055 MW.

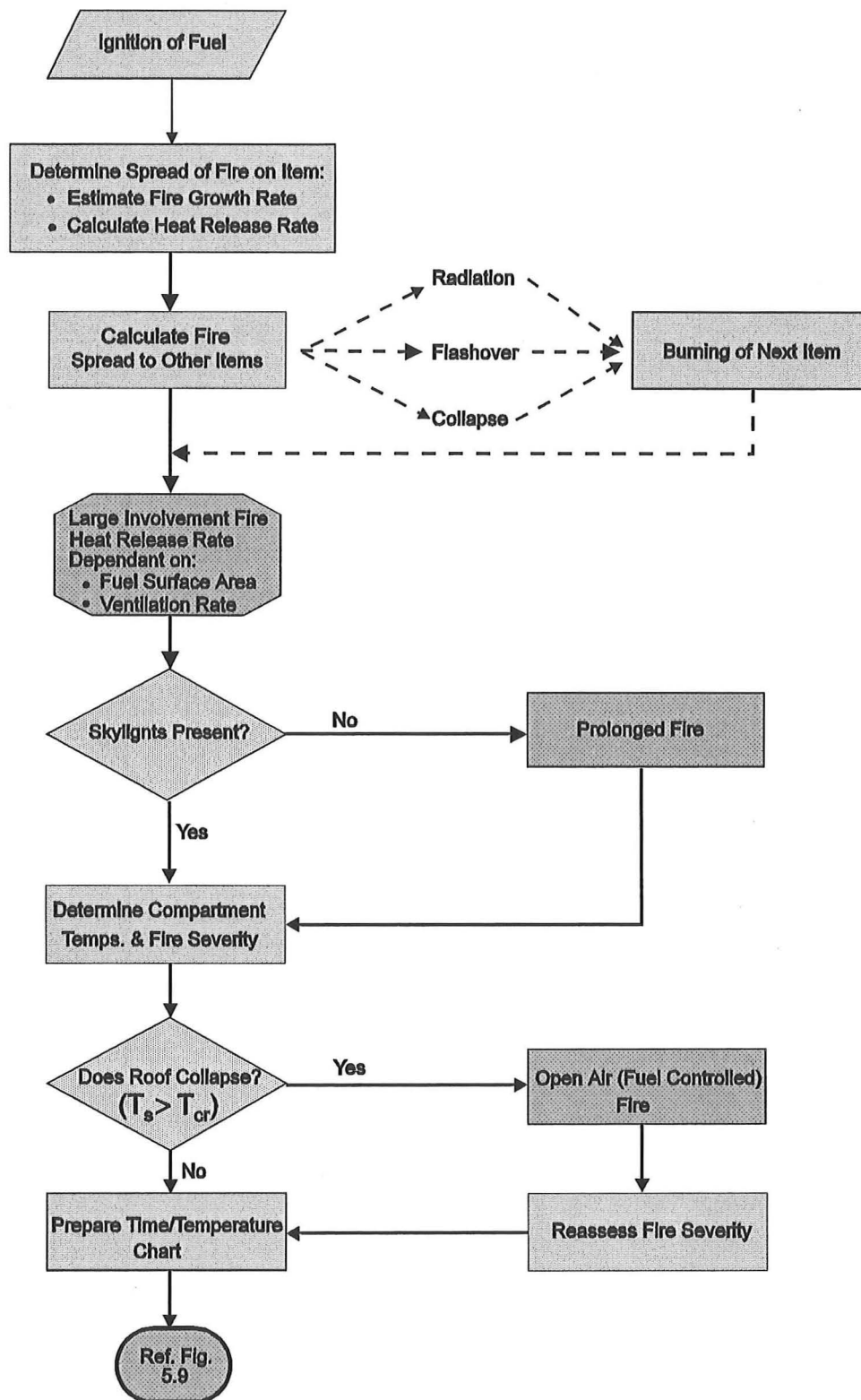


Fig. 5.6 : Fire Design Procedure - Fire Growth and Spread

## 5.5 Fire Spread

Figure 5.6 continues the fire growth phase into fire spread onto adjacent fuel items and then full involvement within the compartment. The important conclusion is a time/HRR graph for use in determining fire resistance and the effect of Fire Service response. Discussing each step in turn:

5. For a given ignition location, use FPETOOL “Freeburn” to simulate fire spread between fuel items, based on radiation. Otherwise an approximation can be achieved by assuming that all fuel has one standard growth rate. The maximum heat release rate can be assumed to be ventilation controlled as follows:

$$Q_v = m_b h_a / 60 \quad (\text{kW}) \quad [5.1]$$

$$\begin{aligned} Q_v &= \text{ventilation controlled HRR (MW)} \\ h_a &= \text{calorific value of fuel (MJ/kg)} \\ m_b &= \text{burning rate (based on wood)} \\ &= 5.5 A_v H_o^{1/2} \quad (\text{kg/s}) \end{aligned} \quad [5.2]$$

$$[m_b = m_{\text{air}} / r; (r_{\text{wood}} \approx 5.7 \text{ kg/kg}) - \text{ref. eqn 5.7}]$$

The time to reach this heat release rate ( $t_g$ ) is:

$$t_g = (Q_v)^{0.5} t_s \quad (\text{s}) \quad [5.3]$$

$$t_s = \text{standard fire growth time to reach 1.055 MW (s)}$$

The energy released ( $E$ ) to reach the peak heat release rate is:

$$E = (t_g Q_v) / 3 \quad (\text{MJ}) \quad [5.4]$$

6. If this programme indicates that due to separation distances, fire spread will not occur, then simulate a compartment fire with FPETOOL “Fire Simulator” or CFAST based on the most hazardous fuel load item. This will indicate whether fire spread will occur between fuel items due to flashover (compartment temperature exceeding 600°C). Amend the fire growth files to reflect this outcome if valid. Carry out manual calculations to verify results in broad terms.
7. Cross-check the flashover condition by applying Thomas’s flashover correlation [Walton/Thomas, 1992]:

$$Q_{FO} = 0.0078 A_T + 0.378 A_v \sqrt{H} \quad [5.5]$$

- $A_T$  = internal surface area of compartment ( $m^2$ )
- $A_v$  = area of vertical openings ( $m^2$ )
- $H$  = average height of openings (m)
- $Q_{FO}$  = minimum HRR for flashover (MW)

$Q_{FO}$  can be compared to the maximum heat release rate expected before a flashover condition.

8. If flashover or full involvement does not occur then the fire duration is based on the burning rate for the fuel over the exposed surface area acting on the mass of fuel identified as burning:

$$t_B = M_F / (m_{SF} \cdot A_s) \quad [5.6]$$

- $t_B$  = time for burning in steady state (s)
- $M_F$  = mass of fuel (kg)
- $m_{SF}$  = specific burn rate of fuel ( $kg/s.m^2$ ) [ref. Tewarson, 1992]
- $A_s$  = specific surface area of fuel ( $m^2$ ) [refer Fire Engineering Design Guide - Buchanan, 1994]

This time ( $t_B$ ) should only apply to the steady state condition, although it often includes the decay stage. The growth phase is added to this time.

9. If flashover does occur, then for a fully developed fire, a check can be made to establish whether it is ventilation or fuel controlled. The following relationship holds true for ventilation controlled fires [Drysdale, 1985]:

$$m_F > m_{air} / r_F \quad [5.7]$$

- $m_F$  = burning rate of fuel (kg/s)
- $m_{air}$  = burning rate for ventilation controlled fires (kg/s)
- $r_F$  = stoichiometric air/fuel ratio [ref. Drysdale, 1985]

$$m_{air} = 0.52 A_W H_o^{1/2} \quad [5.8]$$

- $A_W$  = area of ventilation openings ( $m^2$ )
- $H_o$  = height of openings (m)

10. If the roof is likely to remain in place, equivalent fire severity times can then be calculated based on the ventilation or fuel controlled regimes [Buchanan, 1994]:

i) Ventilation Controlled

$$t_e = e_f k_b w_f \quad [5.9]$$

$t_e$  = equivalent fire severity (min.)

$e_f$  = fire load (MJ/m<sup>2</sup>)

$w_f$  = ventilation factor

$k_b$  = conversion factor:

$\sqrt{\lambda \rho c}$ (J/m <sup>2</sup> Ks <sup>1/2</sup> )	TYPICAL CONSTRUCTION	$k_b$ (min. m <sup>2.3</sup> /MJ)
< 720	Insulating material	0.080
720 to 2500	Concrete or plasterboard	0.055
> 2500	Thin steel	0.045

$\lambda$  = thermal conductivity (W/mK)

$\rho$  = density (kg/m<sup>3</sup>)

$c$  = specific heat (J/kg K)

The ventilation factor is given by:

$$w_f = \left[ \frac{6.0}{H_f} \right]^{0.3} \left[ 0.62 + \frac{90(0.4 - \alpha_v)^4}{1 + b_v \alpha_h} \right] > 0.5 \quad (\text{m}^{-0.3}) \quad [5.10]$$

where  $\alpha_v = A_v/A_f$  0.05 ≤  $\alpha_v$  ≤ 0.25 [5.11]

$\alpha_h = A_h/A_f$   $\alpha_h$  ≤ 0.20 [5.12]

$b_v = 12.5 (1 + 10 \alpha_v - \alpha_v^2)$  [5.13]

$A_f$  = firecell floor area (m<sup>2</sup>)

$A_v$  = area of vertical window and door openings (m<sup>2</sup>)

$A_h$  = area of horizontal openings in the roof (m<sup>2</sup>)

$H_f$  = height of firecell (m)

ii) Fuel Controlled - refer equation [5.6] for  $t_B$

11. Compartment temperatures (T) can be calculated for ventilation controlled fires, using the following relationship from Lie [1992]:

$$T = 250(10F)^{0.1/F} e^{-F^2 t} [3(1 - e^{-0.6t}) - (1 - e^{-3t}) + 4(1 - e^{-12t})] + C \left[ \frac{600}{F} \right]^{0.5} \quad [5.14]$$

$F$  = opening factor (m<sup>1/2</sup>) =  $A_v H_o^{0.5} / A_T$

$t$  = burn time (hrs), where the relationship is valid for:

$$t \leq (0.08 / F) + 1 \text{ and } 0.01 \leq F \leq 0.15$$

$C$  = 1 for light materials ( $\rho < 1600$  kg/m<sup>2</sup>) and 0 for heavy materials ( $\rho \geq 1600$  kg/m<sup>2</sup>).

Otherwise refer to time-temperature curves for various fuel loads and opening factors. These are shown in 'An Introduction to Fire Dynamics' (Figure 10.19, Drysdale, 1985)

12. In the event of roof collapse, the duration of an open air fire can be determined using equation 5.6 or through relating remaining fuel energy levels to the estimated heat release rate of the fuel [Buchanan, 1994]:

$$t_B = E / Q_f \quad [5.15]$$

$t_B$  = time for burning in steady state (s)

$E$  = energy in unburnt fuel (MJ)

$Q_f$  = heat release rate of fire (MW)

13. The various time versus heat release rate relationships can be used at different stages of fire development for example:

- Fire growth; refer to the output from 'Freeburn', or apply the relationships given in equations 5.1 to 5.4.
- Steady state condition; enclosed compartment - the equivalent fire severity times can be based on the ventilation openings, and possibly allowing for the reduction in fuel burnt during the growth stage. Refer equation 5.5 for calculating  $t_e$ , and equation 5.14 for the energy released at the end of the growth stage.

The compartment temperature should be monitored against time to determine whether other ventilation openings will occur, such as skylights melting or windows breaking. These events will affect the fire severity, and they can be mapped on a time versus HRR chart as an increase in the heat release rate. Equation 5.5 should be reapplied for the new ventilation factor.

- Steady state condition; roof collapse - the fire can now be modelled as an open air fire, with the time for burn out based on the burning rate of the fuel, or the remaining energy levels (refer equations 5.6 or 5.15). Roof collapse is expected to occur when the roof support structure fails. This will be due to either wooden purlins burning to an extent where they cannot continue to support the roof cover, or steel portals (or rafters) are heated to a point where they lose their design strength and collapse under the roof weight.
- Decay phase - this period of fire development is recognised as being very difficult to model [Lie, 1992]. Unpredictable parameters such as wind, water, debris, and remaining fuel load result in a chaotic conclusion to a fire. However, the influence of the decay period to the overall fire severity is not considered significant so approximations are adequate.



### 5.6 Worked Example : Manual Calculations

Consider a warehouse storing PVC bottles as shown in Fig. 5.7. The objective is to establish a time versus HRR profile for a fully involved fire, assuming a fire starts in a single rack when both doors are open.

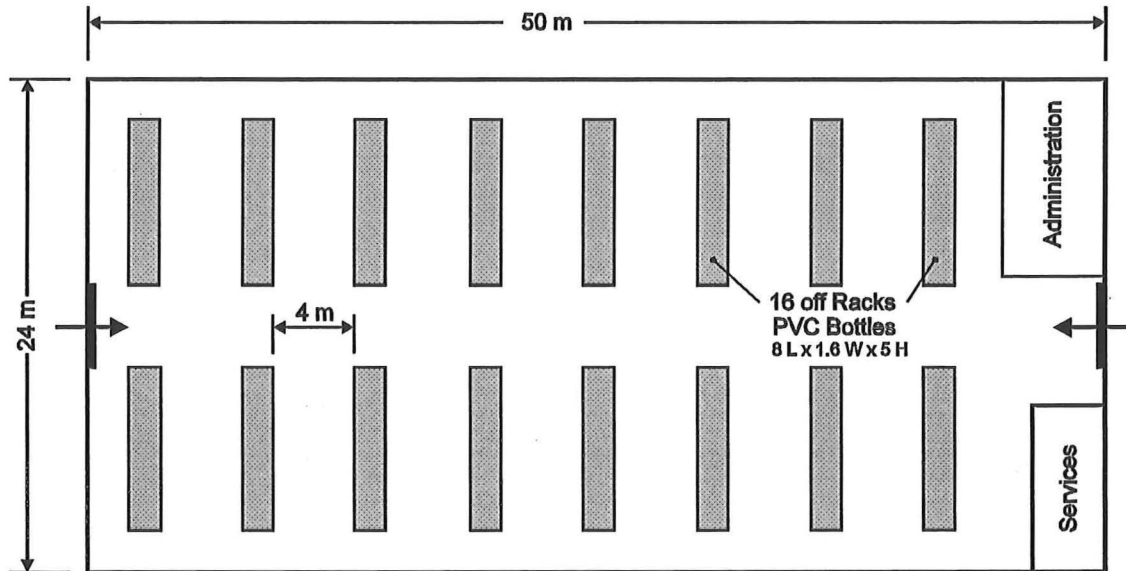


Fig. 5.7 : Warehouse Storing PVC Bottles

#### 1. Complete schedule of fuel:

- Description : PVC Bottles occupying 16 racks @ 8 m long x 1.6 m wide x 5 m high.
- Mass : 1 Rack =  $(8 \times 5 \times 1.6) \times 100 \text{ kg/m}^3$  (est.)  
= 6400 kg per rack.
- Surface Area : 1 Rack =  $(8 \times 5 \times 2) + (1.6 \times 5 \times 2) + (1.6 \times 8)$   
= 108.8 m<sup>2</sup> per rack.
- Calorific Value : CV = 17.8 MJ/kg
- Total Energy : 1 Rack =  $17.8 \times 6400 = 114,000 \text{ MJ}$   
Total Load =  $114,000 \times 16 = 1,824,000 \text{ MJ}$
- Peak HRR :  $Q_f = 2.84 \text{ MW/m}^2$  [NFPA 92B]
- Peak HRR per rack :  $Q_f = 2.84 \times (8 \times 1.6) = 36.4 \text{ MW}$
- Growth Rate :  $t_s = 75 \text{ s}$  (very fast)
- Time to peak HRR [5.3] :  $t_g = (36.4)^{0.5} \cdot 75 = 452 \text{ s}$

## 2. Building Geometry

- Vertical Vents = 2 openings measuring 4 x 4 m  
= 32 m<sup>2</sup>
- Horizontal Vents = 8 skylights x 24 m x 2 m wide  
= 384 m<sup>2</sup>
- Floor Area = 1200 m<sup>2</sup>
- Firecell Height = 8 m

## 3. Calculate fire load energy density:

$$\begin{aligned}\text{FLED} &= (114,000 \text{ MJ} \times 16 \text{ racks}) / 1200 \text{ m}^2 \\ &= 1520 \text{ MJ/m}^2\end{aligned}$$

this figure is typical of a warehouse type occupancy.

## 4. Spread of Fire to Neighbouring Racks : From the program 'Radiation Ignition of an Adjacent Fuel' in FIRECALC, an estimation can be made of the minimum heat flux required to ignite neighbouring racks.

$$\begin{aligned}\text{Rack separation} &= 4 \text{ m} - 1 \text{ m (flame projection)} \\ &= 3 \text{ m}\end{aligned}$$

If the minimum radiation flux to ignite a neighbouring rack is 20 kW/m<sup>2</sup>, FIRECALC shows that **524 kW/m<sup>2</sup>** irradiation is required from the burning object.

From Drysdale [1985] an estimate can be established for net emissive power from one face of a burning object. Using the formula:

$$E = 1/2 (0.3 \text{ m}'' \Delta H_c A_f / l D) \quad [5.16]$$

$E$  = net emissive power

$\text{m}''$  = mass burn rate

$\Delta H_c$  = heat of combustion (17.8 MJ/kg)

$A_f$  = surface area of fuel (108.8 m<sup>2</sup>)

$l$  = flame height (5 m [estimated])

$D$  = width of fuel face (8 m)

Firstly calculating the mass burn rate:

$$\begin{aligned}\text{m}'' &= (Q_f / A_f) / \Delta H_c \\ &= (36.4 \text{ MW} / 108.8 \text{ m}^2) / 17.8 \text{ MJ/kg} \\ &= 0.019 \text{ kg/s.m}^2\end{aligned}$$

$$\therefore E = 1/2 \times (0.3 \times 0.019 \times 17.8 \times 10^3 \times 108.8) / (5 \times 8)$$

$$\text{Net emissive power from example rack} = \mathbf{138 \text{ kW/m}^2}$$

This implies that fire spread is not expected before total involvement of the rack. Once the design rack is fully involved (ie. after 452 s), there is the possibility of fuel collapse on to neighbouring racks.

5. Check compartment temperature after 452 s (refer eqn. 5.14]:

$$t = 0.125 \text{ hrs}$$

$$F = A_v H_o^{0.5} / A_T = 0.053 \text{ m}^{1/2}; 0.01 \leq F \leq 0.15 \text{ so OK.}$$

$$(0.08 / F) + 1 = 2.5 \text{ hrs; and } t < 2.5 \text{ hrs so OK.}$$

Applying equation [5.14] results in  $T = 646^\circ\text{C}$ , and this implies that flashover occurs around the time of full involvement of a rack, although this relationship is for ventilation controlled fires.

6. Check whether the fire is ventilation controlled before flashover occurs:

$$\text{applying eqn. [5.1]: } Q_v = m_b h_a / 60$$

$$m_b = 5.5 \cdot A_v \cdot H_o^{0.5} = 352 \text{ kg/s}$$

$$\therefore Q_v = 104 \text{ MW}$$

this implies that a fire will only become ventilation controlled, given that vertical openings =  $32 \text{ m}^2$ , if the HRR is 104 MW. The HRR at the end of the growth stage is therefore 36.4 MW.

7. Recheck whether there is sufficient heat output for flashover, applying equation 5.5:

$$Q_{FO} = 0.0078 A_T + 0.378 A_v H^{0.5}$$

$$= 33.5 \text{ MW}$$

$\Rightarrow$  flashover is expected to occur once the fire has grown to 33.5 MW (ie. after 435 s). The approximation of 450 s is therefore considered adequate.

8. At the time of flashover it is expected that the skylights will melt out and roof venting will occur. Calculating the equivalent fire severity (eqn. [5.9]):

$$t_e = k_b e_f w_f$$

$$\therefore t_e = 0.055 \times 1520 \times 0.832$$

$$= 69.5 \text{ min.}$$

$$\alpha_v = A_v / A_f = 0.027 : \text{let} = 0.05$$

$$\alpha_h = A_H / A_f = 0.32 : \text{let} = 0.20$$

$$b_v = 12.5 (1 + 10\alpha_v - \alpha_v^2) = 18.7$$

$$\therefore w_f = 0.832 \text{ m}^{-0.3}$$

9. The equivalent rate of heat release is:

$$Q_e = 1,824,000 / (69.5 \times 60) = 437 \text{ MW}$$

10. Assume roof collapse occurs after 25 minutes (refer to the FEDG [Buchanan, 1994] for calculations for determining failure of steel structures):

$$\begin{aligned} \text{Energy burnt after 25 minutes} &= 437 \text{ MW} \times 25 \text{ min.} \times 60 \text{ s} \\ &= 655,500 \text{ MJ} \end{aligned}$$

$$\therefore \text{Energy left} = 1,168,500 \text{ MJ}$$

$$\begin{aligned} \text{Open air heat release rate} &= 36.4 \text{ MW/rack} \times 16 \text{ racks} \\ &= 582 \text{ MW} \end{aligned}$$

$$\begin{aligned} \Rightarrow \text{Burn Time for an Open Air Fire:} \\ &= 1,168,500 \text{ MJ} / 582 \text{ MW} \\ &= 2008 \text{ s (33.5 min)} \end{aligned}$$

11. Total burn time:

$$\begin{aligned} t_T &= 452 \text{ s (growth phase)} + 1048 \text{ s (ventilation controlled steady state phase)} + 2008 \text{ s (open air steady state and decay)} \\ &= 3508 \text{ s (58.5 mins} \Rightarrow 60 \text{ minute fire rating is adequate)} \end{aligned}$$

12. Resulting time versus HRR chart:

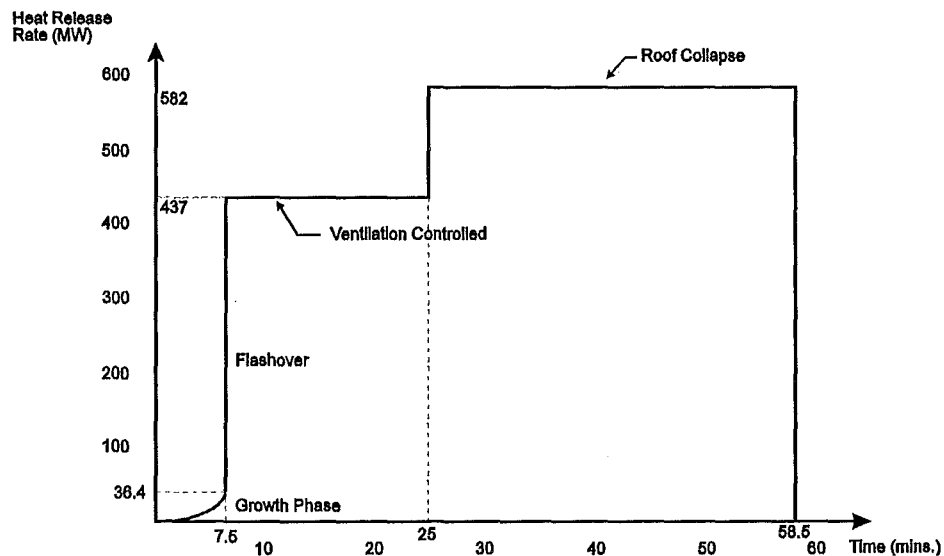


Fig. 5.8 : Time versus Heat Release Rate for Worked Example

## 5.7 Boundary Exposures and Radiation

The following flow charts (Figs. 5.9 and 5.11) show the next steps in the fire design procedure for determining boundary exposure. Attention is given to the role of the Fire Service and fire detection/suppression systems in controlling this risk; where these design issues are discussed in sections 7 and 10 and the problem of equating water usage to heat output (and emitted radiation) is evaluated in section 11.

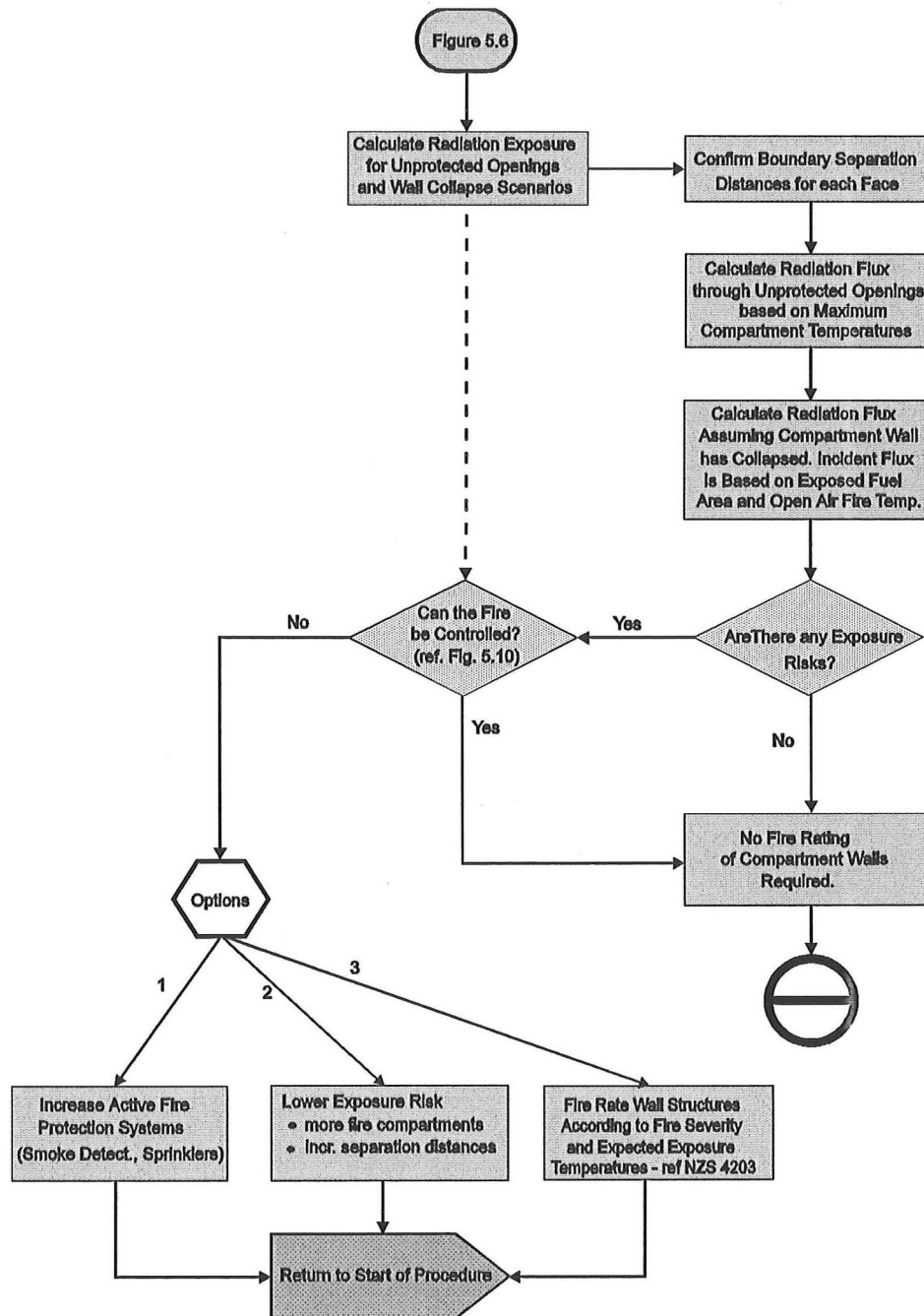


Fig. 5.9 : Fire Design Procedure - Radiation Exposure

### 5.7.1 Radiation to Neighbouring Risk

A fire within a building can spread to a neighbouring property by either radiation or 'flying brands'. Fire spread by 'flying brands' is subject to wind directions and the nature of the burning product. The more probable method of fire spread is by radiation.

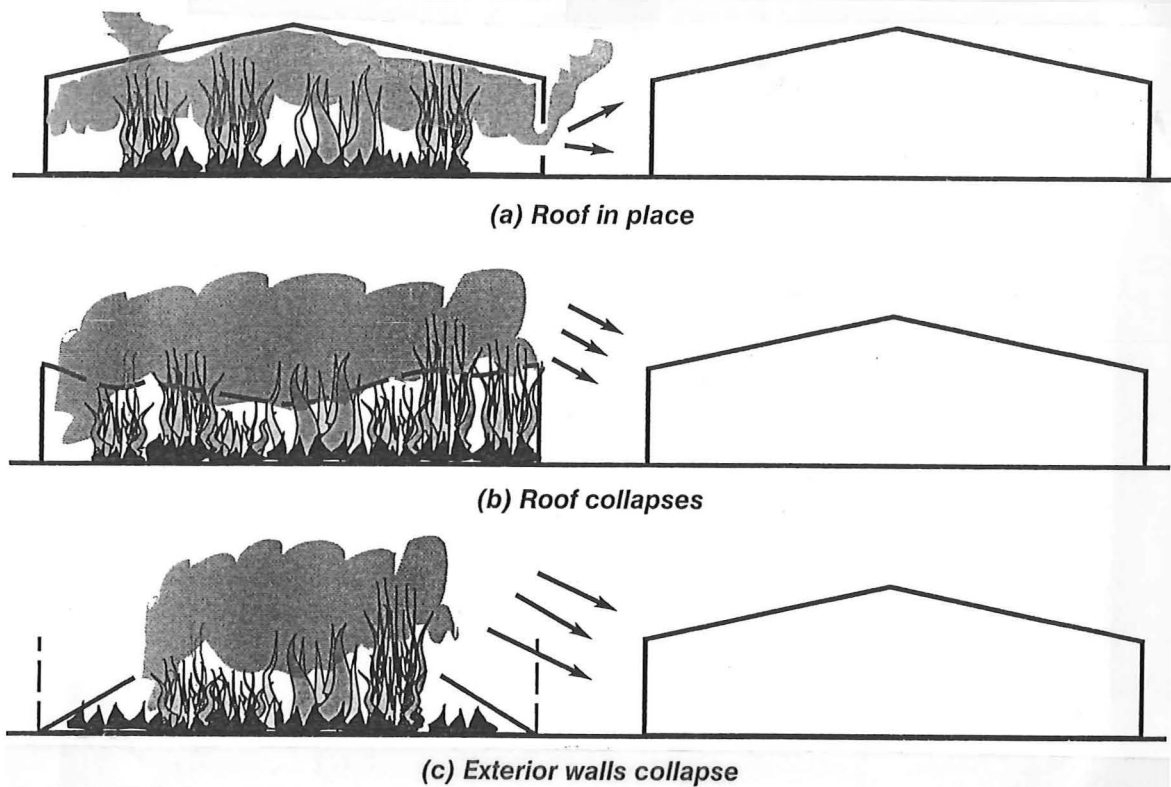


Figure 5.10 : Fire Spread by Radiation

### 5.7.2 Critical Radiation Intensity

A key factor with radiative fire spread is the critical ignition intensity of the receiving surface. Table 5.1 summarises values taken from a variety of sources [Lie, 1972; SANZ, 1988; Buchanan, 1994].

The values usually adopted are for the pilot ignition scenario. This coincides with the fire spread risk of flying brands. It follows that if the received radiation on a surface is above the critical radiation intensity, then ignition is expected to occur. This outcome depends on separation distance, material (combustible or non-combustible), and whether any prewetting of the received surface is occurring.

Material	Critical Intensity (kW/m <sup>2</sup> )	
	Pilot Ignition	Spontaneous Ignition
Wood	14.6	29.3
Wood with common paint	16.7	23-50
Fibre insulating board	6.3	-
Fibre insulating board - fire retardant treated	8 - 42	-
Bitumen Roof	-	-
Aluminium Roof	-	-
Cotton Fabric	13	25
Non-combustible wall with non-fire resistant glazing	20	-
Non-combustible wall fitted with fire rated glazing	50	-

Table 5.1 : Critical Radiation Intensities for Various Materials

### 5.7.3 Calculation of Radiant Heat Flux

The effects of radiation from a fire within an industrial building on a neighbouring building can be calculated under the following circumstances:

- Through unprotected openings; refer equation 11.3. CSIRO [1991] states that a typical value for a fire compartment temperature, as required in this equation, is around 1000°C.
- Flame exposure above wall line or through collapse of the external wall. Drysdale [1985] provided relationships for radiant heat flux received from a flame assuming a point source and rectangular source:

i) Point Source -  $Q_R = (0.3 Q_T \cos \phi) / 4.\pi.R^2$  (kW/m<sup>2</sup>) [5.17]

$Q_T$  = total design heat load (kW)

$\phi$  = angle between the receiver and the flame point source.

$R$  = distance from the point source to the receiver (m)

ii) Rectangular Source -  $Q_R = 0.15 \phi Q_T / (l D_f)$  (kW/m<sup>2</sup>) [5.18]

$\phi$  = configuration factor

$l$  = flame height (m)

$D$  = width of flame (m)

Note: Flame height (l) =  $0.23 Q_c^{2/5} - 1.02 D_f$  (m) [5.19]

$Q_c$  = convective heat ( $\approx 0.7 Q_T$ )

- Receiving surface has a critical radiation intensity based on pilot ignition, below the radiant heat flux.

Examples showing application of these equations and the cooling power of water to control the effects of radiation, are given in Section 11.0 'Fire Fighting Design'.

## 5.8 *Fire Control Measures*

Figure 5.11 shows the design procedure for determining the necessary fire control measures. A key factor in this evaluation is the level of exposure risk. If the estimated radiation to neighbouring boundaries under worst case scenarios does not result in an exposure risk, then the emphasis on fire control may be reduced.

Where water application is necessary to ensure the fire is contained, then the fire safety design must prove the capabilities of either a sprinkler system or Fire Service response. These design areas are discussed further in sections 7.0 and 11.0.

## 5.9 *Conclusions*

1. The aim of this section is to provide a suitable fire design procedure for single storey industrial buildings. The minimum fire safety goals are life safety, protection of neighbouring property and safety of Fire Service personnel.
2. A fire design procedure assists in the evaluation of:
  - fire growth
  - fire spread within the firecell
  - open air burning following roof collapse
  - boundary exposure
3. The effect of active and passive fire protection systems on a design fire can be also be evaluated to identify benefits.
4. An important component in modelling fire development is a time/HRR graph to determine boundary exposure, and the effect of Fire Service response.
5. Radiant heat flux calculations can be performed to assess whether fire fighting water is required to control fire spread to neighbouring property.



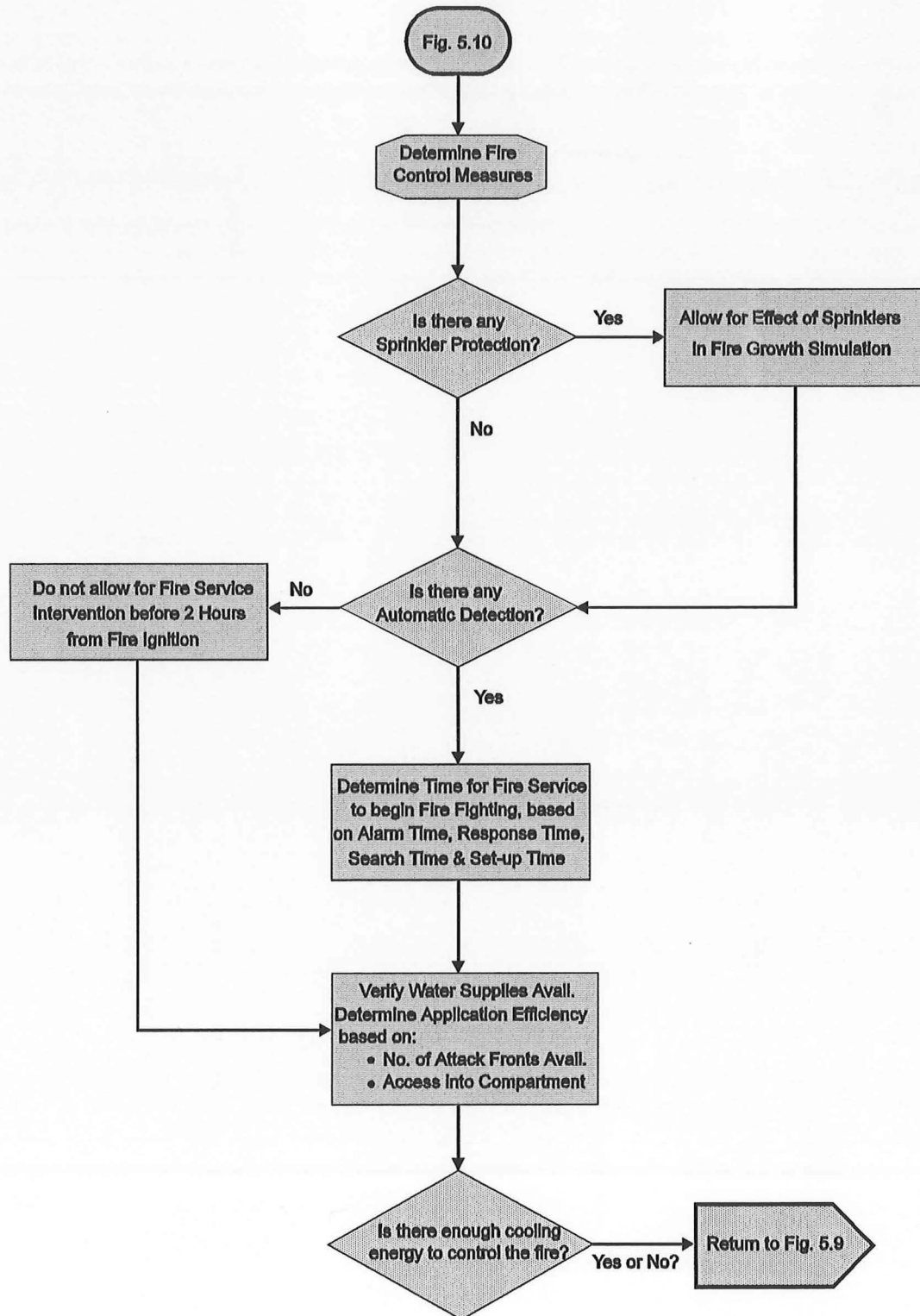


Fig. 5.11 : Fire Design Procedure - Fire Control Measures

## 6.0 LIFE SAFETY

### 6.1 Objectives

A primary aim in fire engineering is ensuring people are safeguarded from injury or illness in the event of a fire. This applies to any occupancy, although the methods employed will differ for a warehouse as opposed to a prison or a shopping mall. There are five key occupancy factors influencing life safety design [Sime, 1994 a]:

- numbers
- familiarity
- sleeping risk
- mobility
- response to fire alarm

The objective in life safety design is to ensure that building occupants either escape, are rescued or find a place of refuge before untenable conditions occur. This is clearly stated in the New Zealand Building Code Clause C2 : Means of Escape [BIA, 1991]:

- [Clause C2.1(a) - Objective] ‘to safeguard people from injury or illness from a *fire* while escaping to a *safe place*’
- [Clause C2.2(a) - Functional Requirement] ‘*Buildings* shall be provided with *escape routes* which give people *adequate* time to reach a *safe place* without being overcome by the effects of *fire*’

Obviously the preferred outcome is escape, but factors may necessitate rescue or refuge, such as building layout, building use (hospital, high security), or the disability of occupants. For industrial buildings the occupants are expected to be alert, active and mobile, and the evacuation procedure is based on people escaping.

The NZ Building Code also places an emphasis on protection of fire service personnel during rescue operations, where this is reflected in the use of safe paths plus selected fire ratings for firecells.

### 6.2 Escape Behaviour

In designing an acceptable escape system the following occupancy variables need to be ascertained [Sime, 1994 a]:

1. Role in occupancy (staff versus public; sleeping versus non-sleeping).
2. Escape route familiarity and building layout.
3. Site evacuation schemes and training.
4. Group dynamics and attachments.
5. Characteristics such as age, infirmity and disability.
6. Location and proximity to exit.
7. Information and communication on fire in progress.
8. Smoke obscuration (visibility, irritancy and toxicity).
9. Fire characteristics (heat and smell).
10. Exit signs.
11. Light levels and light sources.

These factors collectively determine the escape time to a safe place. Establishing values for some factors such as the worth of a site evacuation scheme, or the influence of age, is very difficult. A design method is provided in section 6.3 that attempts to integrate behavioural and deterministic 'values'.

### 6.3 Design Process

Figure 6.1 shows a flow chart summarising the process in determining whether a designed escape system is adequate. This process places an emphasis on the following factors:

- Type of alarm and time to detection of fire.
- Fire growth and time to untenable conditions.
- Occupant response, preparation and avoidance time.

The evacuation process is shown on the flow chart to involve a number of stages. These are reflected in the following relationship:

$$T_{ae} = t_d + t_r + t_E \quad [6.1]$$

$$\text{where } t_E = (t_p + t_a)/e \quad [6.2]$$

(also refer section 6.5)

$T_{ae}$  = total evacuation time (s)

$t_d$  = detection time (s)

$t_r$  = response time (s)

$t_E$  = escape time (s)

$t_p$  = preparation time (s)

$t_a$  = avoidance time (s)

$e$  = avoidance efficiency

Response time for occupants varies according to factors such as the cue received to evacuate, group dynamics, training and commitment to duties. Preparation time involves actions taken before evacuating such as investigating the fire, rescuing, fighting the fire, and retrieving property. These variables are discussed further in section 6.5.

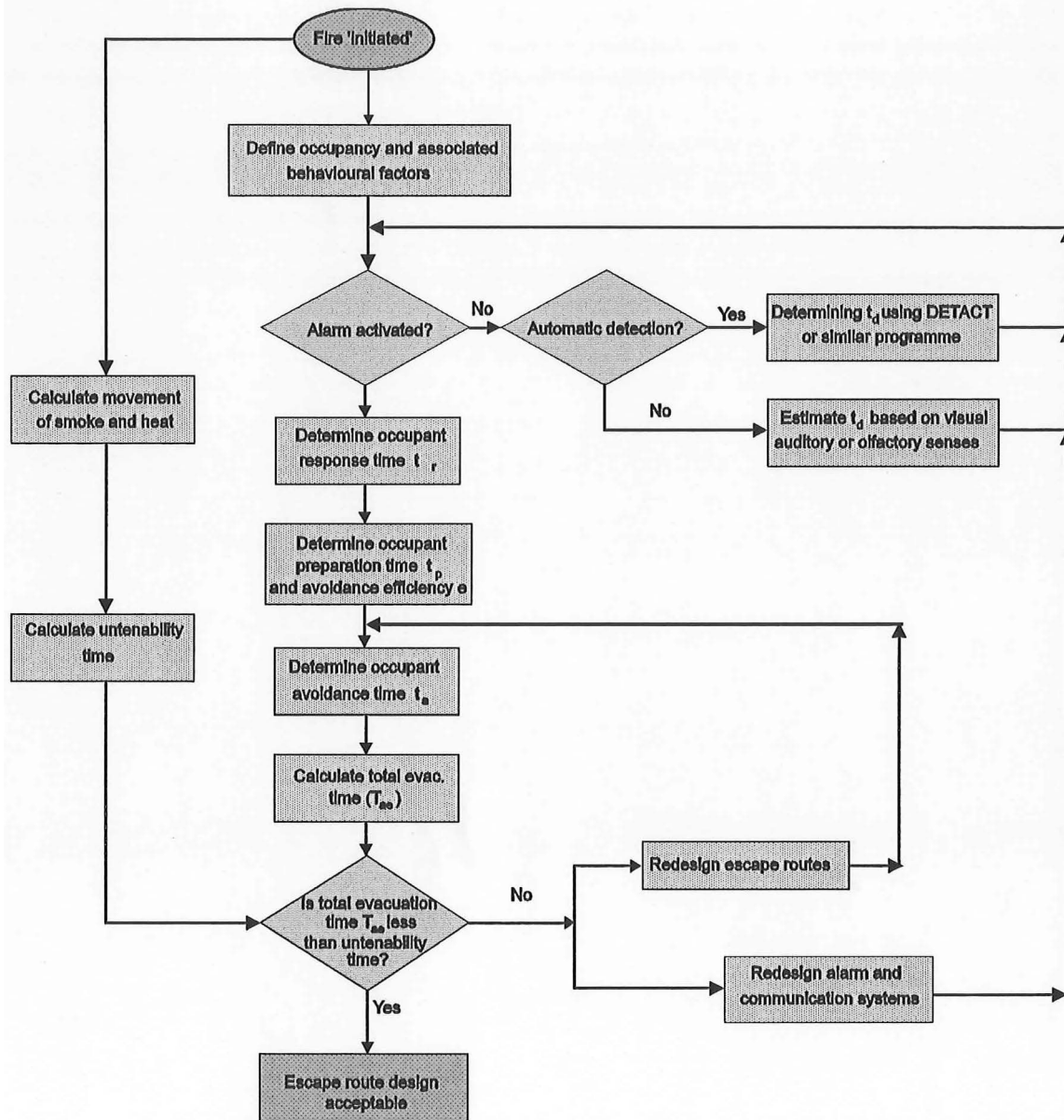


Fig. 6.1 : Flow Chart, Design of Escape Route Systems

Note that a safety factor is not used as recommended in the Fire Engineering Design Guide [Buchanan, 1994]. A safety factor would be necessary if the calculated evacuation time and untenability time were both at their most likely values in the event of a typical fire. However, the evacuation time calculated using the technique in this paper is considered to be at the high end of the expected range of evacuation times, and the time to untenability is considered to be at the low end

(rapid fire growth end) of expected untenability times. This means that the tails of the distributions are being compared (not a comparison of mean or expected values) so an additional safety factor is not necessary.

#### **6.4 Prescriptive Solutions**

Prescriptive design methods such as the New Zealand Building Code Acceptable Solutions, are based on movement theory and have limited reference to behavioural features. Sime [1994 a] defines this approach as the 'Model A' method which is based on the following assumptions:

1. People's safety cannot be guaranteed due to potential panic and unpredictable escape behaviour.
2. Individuals start to move as soon as they hear an alarm.
3. Floor clearance is primarily dependant on the time it takes to move to and through an exit.
4. Movement in fires is characterised by the aim of escaping.
5. People are most likely to move towards the exit to which they are nearest.
6. Fire exit signs ensure people find a safe escape route.
7. People are unlikely to use a smoke filled escape route.
8. All the people present are equally capable of physically moving to an exit.

This prescriptive approach is often conservative in determining acceptable travel speeds, available exits, and limits on vertical travel. The assumed time for untenable conditions is usually 2.5 minutes [Pauls, 1992; Buchanan, 1994]. Even with this approach, the level of risk is indeterminate and the relative level of safety is unclear.

#### **6.5 Behavioural Solution**

The alternate design method is referred to as 'Model B' or the behavioural solution [Sime, 1994 a]. This approach acknowledges the unique behaviour of people in an emergency [Pauls, 1992]:

1. People do not often panic; behaviour tends to be altruistic and reasonable. Any panic is more likely to be caused by delays in people receiving relevant information.
2. A central motivation and activity in fires is to seek information including news on the fire itself and how other people are coping.
3. Evacuation, and response to fire generally, is often a social response.

4. Fire alarm sirens cannot always be relied upon to prompt people to move immediately to safety
5. As long as an exit is not obstructed, people tend to move in a familiar direction, even if further away, rather than use an unfamiliar fire escape route.
6. Fire exit signs are not always noticed and may not always overcome difficulties in orientation and wayfinding imposed on escapes by the architectural layout and design of an escape route.
7. People are often prepared, if necessary, to move through smoke.
8. People's ability to move towards an exit may vary considerably, depending on age, mobility, confidence etc.

### ***Evacuation Stages***

Methods have been developed to try and quantify this wide range of behaviour. The proposed escape time process is expressed in Figure 6.1, and Equations 6.1 and 6.2. The total evacuation time calculated has to be compared to the untenability time for the design space, as discussed in section 6.6.

**Detection** time ( $t_d$ ) is reasonably easy to determine if automatic alarms are present. A computer programme such as DETACT [FPETOOL, 1994] can determine this time given that the design fire is known as well as the characteristics of the detectors.

As discussed in Chapter 2, very few industrial complexes involved in fires have automatic alarms. The Australian Draft National Building Fire Safety Systems Code [BRRTF, 1991] provides criteria to determine the estimated time for detection based on people acting as the sensors:

- Either
1. Visual and olfactory - time at which the upper layer in the relevant enclosure equals  $0.95 \times \text{room height}$ .
  - or 2. Auditory (ie. sound of a fire) inside enclosure of fire origin - time at which the upper layer in the enclosure of fire origin equals  $0.95 \times \text{room height}$ .
  - or 3. Auditory outside enclosure of fire origin - time at which the temperature in the upper layer in the enclosure of fire origin equals  $450^\circ\text{C}$

Again this depends on the design fire and its behaviour over time.

In determining **response** time ( $t_r$ ), Sime [1994 b] has developed a matrix relating different behavioural features with the expected action for a given occupancy:

ALERTNESS	MOBILITY	SOCIAL AFFILIATION	ROLE	POSITION	COMMITMENT	FOCAL POINT	FAMILIARITY
asleep	low	group	public	lying	high	none	unfamiliar
*	*	*	*	*	*	*	*
**	**	**	**	sitting	**	**	**
***	***	***	***	***	***	***	***
****	****	****	****	standing	****	****	****
*****	*****	*****	*****	*****	*****	*****	*****
awake	high	alone	staff	moving	low	focussed	familiar

Fig. 6.2: Matrix of Factors Influencing Response Time

In this method each category is assessed for the given situation and each 'score' given by the number of stars in Figure 6.2, is summed to give a total. This total is averaged over the 8 categories and a  $W_{\text{eff}}$  value is determined by:

$$W_{\text{eff}} = 5 / \text{Average}$$

The response time is calculated by multiplying this  $W_{\text{eff}}$  value by a factor representing the form of alerting device:

$$T_r = W_{\text{eff}} * w(1,2,3)$$

$w1 = 3$  (alarm bell)  
 $w2 = 2$  (non-directional public address)  
 $w3 = 1$  (directive public address)

Example: Determine the response time for occupants in a warehouse when alerted by alarm bells.

$$\begin{aligned}
 &\text{Total of behavioural factors} = 33 \\
 &\text{Average} = 33 / 8 = 4.125 \\
 &W_{\text{eff}} = 5 / 4.125 = 1.2 \\
 &w1 = 3 \text{ (alarm bells)} \\
 &\therefore T_r = 3.6 \text{ minutes}
 \end{aligned}$$

Limited information is available on determining the **preparation** time ( $t_p$ ). This is a measure of time associated with investigation and alternative actions to evacuation. The Fire Engineering Design Guide [Buchanan, 1994] recommends that a minimum of 30 seconds is allocated to this variable.

The **avoidance** time ( $t_a$ ) is simply the travel time. A computer program such as EVACNET+ [1984], or 'Egress Times' [FIRECALC, 1993] can calculate this time. Alternatively manual calculations based on the effective-width model can be applied [Nelson and MacLennan, 1992].

The Australian Draft National Building Fire Safety Systems Code [BRRTF, 1991] also provides a quantitative solution for determining response time, as well as preparation and avoidance time. An avoidance efficiency is applied to the sum of

the preparation and avoidance time. The following Table shows typical efficiency values from this Code:

BUILDING USE CLASSIFICATION	RESPONSE EFFICIENCY $R_e$	AVOIDANCE EFFICIENCY $e$
Museum, library, courtroom	0.5	0.5
Primary school	0.4	0.4
Secondary school	0.5	0.52
Tertiary school	0.65	0.62
Rest home - asleep & supervised	0.2	0.35
Rest home - awake & supervised	0.4	0.5
Hotels, motels - asleep & unsupervised	0.2	0.24
Hotels, motels - awake & unsupervised	0.5	0.46
Retail shop	0.5	0.6
Offices - procedures	0.7	0.8
Offices - no procedures	0.4	0.4
Industrial operations (incl. utility, defense)	0.66	0.72
Manufacturing and warehouse	0.66	0.72

Table 6.1: Occupant Efficiency Values Based on Occupancy Use

**Example:** Determine the preparation and avoidance time in a warehouse where the avoidance time has been calculated to be 64 seconds using the deterministic escape model EVACNET+.

$$\begin{aligned}\text{Escape Time } (t_p + t_a) &= 30 \text{ (est.)} + 64 \text{ s} \\ &= 94 \text{ s}\end{aligned}$$

$$\text{Avoidance Efficiency } (e) = 0.72 \text{ (from Table 6.1)}$$

$$\begin{aligned}\therefore \text{Actual Avoidance Time} &= 94 / 0.72 \\ &= 130 \text{ s}\end{aligned}$$

## 6.6 *Untenability*

Total evacuation time ( $T_{ae}$ ) must be less than the time for untenable conditions to occur within the design enclosure. The measurement of time is taken from the initiation of the fire, and the anticipated fire behaviour is mapped through growth and steady state conditions as a function of time. Fire simulation programmes such as CFAST are used to model design fires.

A design fire is based on the physical dimensions of the enclosure being studied (ie. a warehouse) and the combustible product expected to be located within. The nature of the product determines the growth rate and fire size; the enclosure layout



and construction determines smoke development and temperature profiles (also refer Sections 1 and 5).

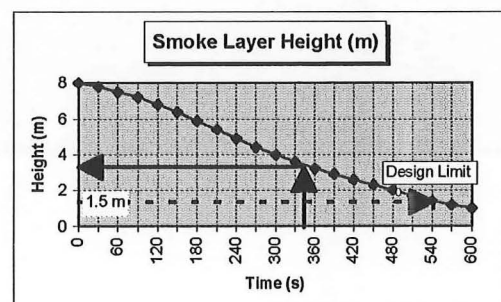
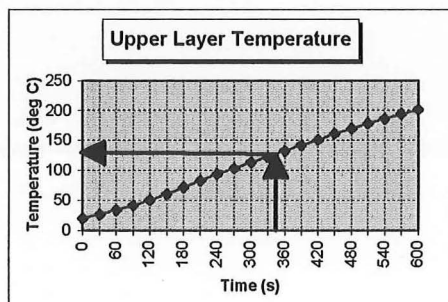
The following Table summarises untenability criteria from two references [BRRTF, 1991; Buchanan, 1994]:

REFERENCE SOURCE	UNTENABILITY CONDITIONS
1. 'Microeconomic Reform : Fire Regulation' BRRTF, 1991.	Smouldering Fire - 2500 ppm CO @ 1.9m above floor Flaming Fire - 100 deg C upper layer temp. @ 1.9m above floor.
2. 'Fire Engineering Design Guide' Buchanan, 1994.	The following criteria apply to the lower gas layer unless the layer height is less or equal to 1.5m :  Convective Heat > 65 deg C Smoke Obscuration < 2m Toxicity : CO > 1400 ppm; HCN > 80 ppm; O <sub>2</sub> > 12% CO <sub>2</sub> > 5% Radiative Heat - the radiative heat from the upper to the lower layer > 2.5 kW/sq m.

Table 6.2: Tenability Limits

**Example:** The following graphs show design fire behaviour for an 8m high warehouse with heat detection but no sprinkler protection. The total escape time is calculated at 346 s. Is the escape system acceptable?

The graphs below show that at 346 s the upper layer temperature is approximately 130 °C and the smoke layer height is 3.2 m. Since the smoke layer height is not down to 1.5 m, the temperature of > 100 °C after 346 s does not affect the egress behaviour. Therefore the escape system is acceptable (assuming the other tenability factors are also within limits).



If the escape route design process concludes that the time to escape is greater than the time to untenable conditions, then either the escape route design has to be

altered or the control of the fire risk has to be improved. Areas that could be modified include:

A) Escape route design:

- i) new exit providing an alternative route.
- ii) reorganising escape routes to shorten travel distances.
- iii) faster detection system.
- iv) creation of smoke-stop or fire resistant escape path.

B) Control of fire risk:

- i) inclusion of active protection system.
- ii) subdivision of spaces into firecells.
- iii) reduction of fire load energy density in design area.
- iv) reorganise combustible loads to minimise rate of fire spread.
- v) improve fire venting options.
- vi) improve emergency response facilities.

Improvements should continue until the maximum escape time is below the minimum time to untenable conditions.

## 6.7 *Industrial Occupancy*

Industrial buildings generally have occupancy and fire safety characteristics that significantly affect a life safety analysis. A life safety system can be designed considering the following points:

1. **Occupancy Classification** : Occupants in industrial buildings are usually employees and are expected to be awake, alert and mobile. High risk occupancy groups (children, infirm people, members of the public, people under detention and sleeping occupants etc.) are not expected to be present in industrial buildings.

Disabled employees requiring assistance during an evacuation should be managed under an evacuation scheme.

2. **Evacuation Schemes** : the Fire Safety and Evacuation of Buildings Regulations 1992 [NZ Government, 1992] requires any unsprinklered place of employment containing more than 10 employees to have a registered evacuation scheme with the NZ Fire Service. If the premises has 10 or less employees and/or is sprinklered then an evacuation procedure is necessary. This is effectively the same as an evacuation scheme except it does not require policing by the Fire Service.

This legal requirement ensures that there is a functional evacuation system in all industrial complexes. The occupants are expected to understand their roles through training plus trial evacuations. This process should reduce the 'response' and 'preparation' times.

3. **Occupancy Numbers** : Generally the occupancy numbers for industrial buildings are low in comparison to occupancies such as commercial offices, retail shops or educational buildings. Occupant densities less than 0.54 persons per square meter allow maximum travel speed during evacuation [Nelson and MacLennan, 1992]. Industrial buildings are usually less than 0.2 persons per square meter, with warehouses at around 0.03 persons per square meter [BIA, 1992].

This reduces concerns with queuing and limited travel speeds in industrial buildings. The NZ Building Code Acceptable Solutions recognises this fact by increasing the allowable travel distance for an open or protected path by 100% if the occupancy density is not greater than 0.05 persons/m<sup>2</sup>. The net effect is a reduced avoidance time and greater spacing of exit points.

Table A1 of the NZBC Acceptable Solutions Fire Safety Annex [BIA, 1992] gives the following occupant densities for 'industrial' buildings. Also included are corresponding values sourced from the equivalent U.K. Building Regulations Acceptable Solutions [Dept. of the Environment and the Welsh Office, 1992].

OCCUPANCY DESCRIPTION	OCCUPANT DENSITY (persons/sq. m) (based on gross floor area)	
	NZBC Acceptable Solutions	UK Acceptable Solutions
Office & Staffrooms	0.1	0.2
Workshops	0.2	0.2
Manufacturing & Process Rooms, Staff Rooms	0.1	0.2
Warehouse Storage	0.03	0.03
Heavy Industry	0.03	?
Bulk Storage	0.01	0.03
Plant Rooms	0.03	?

Table 6.3: Occupant Densities

Note that Table A1 [BIA, 1992] states that for factory space 'in which layout and normal use of fixed equipment or plant determines the number of persons using it in working hours', the design occupancy can be based on actual expected staff numbers.

4. **Building Features** : industrial buildings are invariably large compartments with relatively high ceilings (> 5m). Typical construction details are steel portal frames with either concrete or iron clad walls, and

iron clad roof. There may be mezzanine floors in a portion of the building, plus partitioned office areas but generally the structures are single storey with exits leading directly to outside.

As a result there are large compartment volumes, and untenable conditions take longer to occur than for smaller compartments such as sleeping occupancies or commercial buildings. This allows a greater time period for people to escape from the space, although industrial buildings often require large travel distances to reach a final exit. Escaping direct to outside on the same level also avoids delays associated with stairs.

5. **Building Contents** : industrial buildings generally have high Fire Load Energy Densities (FLED's) with storage facilities usually exceeding 1500 MJ/m<sup>2</sup> [Buchanan, 1994]. This implies that the design fires may reach much greater heat output levels than other occupancies such as accommodation and commercial buildings.

This often results in rapid fire growth rates, large radiation levels, high smoke production rates, and rapid spread of fire. This can negate the advantages of large volume compartments and emphasises the importance of using an accurate fire simulation model, both in terms of input and software.

6. **Active Protection Systems** : as discussed in Section 2.0 - 'Statistical Analysis', most major recorded fires within industrial buildings occur in buildings without active protection systems. This has a serious effect not only on fire control but also the detection time for occupants.

The NZ Building Code Acceptable Solutions [BIA, 1992] do not require a detection system for a high risk industrial building unless more than 100 people are expected within. A manual call point system is only required if more than 50 people occupy the building. This can be at variance to the Fire Safety and Evacuation of Buildings Regulations [NZ Government, 1992], which require an acceptable means of notifying all occupants in an emergency. Unless the open compartment is very small this means that manual call points and sounders are required.

A major concern is the absence of automatic detection systems in industrial buildings, as highlighted in the statistics. A method was given in Section 6.5 for equating expected detection time based on people acting as sensors. This is one area of design that can be improved if the proposed escape features are inadequate for safe evacuation.

## **Support Features**

Acceptable support features of an escape system such as:

- signs
- exit doors
- control of obstructions
- smoke and flame spread control

can be determined through reference to the NZBC Acceptable Solutions [BIA, 1992] or an equivalent document such as the UK Acceptable Solutions [Dept. of the Environment & The Welsh Office, 1992] or NFPA 101 - Life Safety Code [National Fire Protection Assoc., 1991].

## **6.8 Summary**

The objective in life safety design is to ensure that building occupants either escape to a safe place, are rescued, or find a place of refuge before untenable conditions occur. The time required to achieve this objective is influenced by a variety of occupancy factors, such as type of occupancy, layout of exit routes, and group dynamics. Two approaches can be used to design a suitable escape system: a prescriptive or behavioural solution.

Prescriptive solutions are based on movement theory and have limited reference to behavioural features. These solutions are not clear in the level of risk provided, and are generally considered conservative.

Behavioural solutions consider the unique behaviour of people in an emergency. Aspects such as response and preparation for evacuating are heavily influenced by varying human behaviour. Detection times and actual escape times are considered to be non-behavioural, deterministic values. A recommended design process for calculating the expected escape times is the addition of detection, response, preparation and avoidance times.

The total escape times are then compared to the time for untenable conditions to occur. The untenability time is taken from the initiation of the fire and mapped through fire growth and steady state conditions using computer models. If the calculated escape time is greater than the time until untenable conditions then the escape route design will clearly not work. Improvements to the design can be made either through altering the escape route features or improving the control of the fire risk.

In industrial occupancies there are features that differ from other occupancies and influence means of escape analysis. Occupants are expected to be alert, active and

mobile, and be trained in evacuation procedure. Manual alarms are usually present, but not automatic detection systems. Occupancy numbers are low in comparison to other facilities such as schools, shops, and offices, although the combustible risk is usually high (fire load energy density  $> 1500 \text{ MJ/m}^2$ ). The building construction is expected to comprise large open spaces with high ceilings, extending untenability times but resulting in larger escape route distances.

## **6.9 Conclusions**

1. Occupants within industrial occupancies are expected to be alert, active and mobile, plus familiar with their surroundings.
2. One method of designing a suitable escape system is applying a prescriptive solution. These are based on conservative travel speeds, exit configurations and untenability conditions.
3. The recommended design method uses deterministic and behavioural models to compare estimated evacuation time ( $T_{ae}$ ) against the untenability time ( $T_u$ ). The escape route design must prove that  $T_{ae}$  is less than  $T_u$ , otherwise improvements are required.
4. Automatic detection/suppression systems reduce evacuation times as well as improving the likelihood of controlling the fire. They are recommended for inclusion in industrial buildings.

## 7.0 DETECTION AND SPRINKLER SYSTEMS

Sprinkler and detection systems form an integral part of a buildings fire safety strategy. Inclusion of these systems in single storey industrial buildings usually exceeds the minimum Building Code requirements of manual call point systems only.

The aim of this section is to promote the advantages of automatic fire protection and outline appropriate systems for single storey industrial buildings. Emphasis is given to firstly establishing a fire safety strategy, then designing systems to suit.

### 7.1 *Fire Safety Strategy*

A fire safety strategy needs to focus on an overall objective. Schifiliti [1992] defined the three predominant objectives:

1. Life safety.
2. Property protection.
3. Business protection.

#### 7.1.1 *Life Safety*

Designing a life safety system requires early warning of a fire condition. While the ideal option is for automatic detection (such as smoke detectors), the NZBC Acceptable Solutions [1991] only require a manual call point system for single storey industrial buildings. This is on the following provisions and applies to most industrial buildings:

- Occupant numbers are less than 250 people for low to medium hazard activities, and less than 100 people for high hazard activities.
- The buildings are single storey, or contain mezzanine levels that total less than one third of the ground floor space.
- Occupancy is limited to working use.
- Escape routes comply with the exit widths and allowable travel distances to exits.

No fire protection is required if there are less than 50 people in a single storey (low to medium hazard) building. This can be at variance to the Fire Safety and Evacuation of Buildings Regulations [1991], which require an adequate means of alerting all occupants during an emergency. The UK Building Regulations Approved Document B [1992] also expect at the least an effective alarm system:

*'Although there is no requirement under the building regulations to provide a means of giving warning in case of fire, the provision of an appropriate warning system is an essential element in the overall strategy for fire safety in an occupied building.'*

Inclusion of automatic detection or suppression systems enhances life safety, and should be incorporated in building design wherever possible. Operation of these systems will not only provide early warning but also initiate ancillary systems that facilitate safe escape, such as smoke extraction or closing of fire doors.

### 7.1.2 Property Protection

The NZ Building Code requires external property protection where there is risk of a fire spreading to neighbouring properties or to buildings containing certain occupancies. Section 4.0 also discussed the need to minimise environmental damage in the advent of a fire. Further to this a building owner may decide that the complete property, including contents, requires enhanced fire protection and this is included in the site fire safety strategy.

To achieve effective property protection requires at least a detection system. A fire needs to be discovered early enough to allow manual or automatic extinguishment before exceeding unacceptable damage levels. Active fire protection systems can be supplemented with passive systems such as compartmentation and fire resistance rating of the structural components.

In terms of minimum prescriptive requirements, fire compartmentation may become necessary if the NZBC Acceptable Solutions [1991] are applied and there is no sprinkler protection. The Acceptable Solutions place firecell floor area restrictions on different hazard categories:

#### *Clause C3/AS1/3.7.1 Firecell Floor Area Limits*

*... the floor area of an unsprinklered firecell to which an S rating applies, shall not exceed the maximum firecell floor area given in the following table.*

Fire hazard category (ref. Table A1, App. A)	Maximum firecell floor area (m <sup>2</sup> )
1	5000
2	2500
3	1500
4	Specific fire engineering design required



### *Clause C3/AS1/3.7.2*

*In an unsprinklered single floor building where the building elements supporting the roof are not fire rated, the firecell floor area may be unlimited provided that no less than 15% of the roof area (distributed evenly throughout the firecell) is designed for effective fire venting.*

The emphasis with these clauses is on boundary exposure. The firecell floor area can be unlimited if there is no requirement for an S rating. The reference to waiving the floor area limitation for a boundary risk if the roof structure is designed for effective venting, recognises the advantages of releasing heat through the roof and reducing compartment temperatures.

In terms of controlling property damage within a site, compartmentation is very effective for reducing flame, water and smoke damage. The emphasis again returns to effective fire detection and extinguishment to ensure the compartment fire separations remain intact.

#### **7.1.3 Business Protection**

Principles adopted for business protection are similar to property protection although maximum acceptable loss may be viewed differently. The aim is to minimise the effect of fire loss to business operations. The intent is to be able to continue trading after a fire, where this may require not only adequate active and passive fire protection, but also the organisation of the business to ensure sufficient operational resources remain available assuming the worst fire scenario.

There can be advantages to provide active fire protection systems beyond enhanced property and business protection. Construction and insurance costs can be reduced through the combination of active and passive systems. To determine the most cost effective fire safety strategy a site risk assessment should be included as part of the design process.

## **7.2 Detection Systems**

Ramachandran [1981] conducted a study comparing average historical property loss for the textile industry with no detection systems, versus the same fire scenarios with detection systems. He concluded that the fire damage would have reduced by 63% if non-monitored detection systems were included, and 72% if monitored systems were included.

The advantage of a detection system was largely attributable to the earlier response time of the fire service during the growth stages of the fire. The time required for the fire service to travel to the fire scene was the same for protected and non-

protected buildings, however the detection time and the time required to control the fire were less. Also detection systems directly connected to the fire service provided a much lower notification time.

This study highlights the advantage of a detection system for property protection. Sprinklers are a form of detection system but they have the added advantage of actively controlling the fire. It is widely noted that sprinkler protection represents the only probable method of controlling a fire within an industrial complex [Davis & Moore, 1991; Gibson, 1992; Hansell, 1993]. Gibson states:

*... there can be little doubt that the only reliable method of providing fire protection with a reasonable chance of controlling a fire in a warehouse is by installing sprinklers.*

The ability of the fire service to successfully attack and suppress a fire is subject to too many variables to expect this as a probable outcome. However, this possibility can be improved by selecting an automatic detection system to suit the risk.

### 7.2.1 Types of Detection Systems

Fire detection systems fall into four broad categories listed in NFPA 72E [1990]:

- Gas sampling
- Smoke detection
- Flame detection
- Heat detection

Each category has different advantages in cost, maintenance, and effectiveness. Figure 7.1 shows the difference in expected activation times during fire growth.

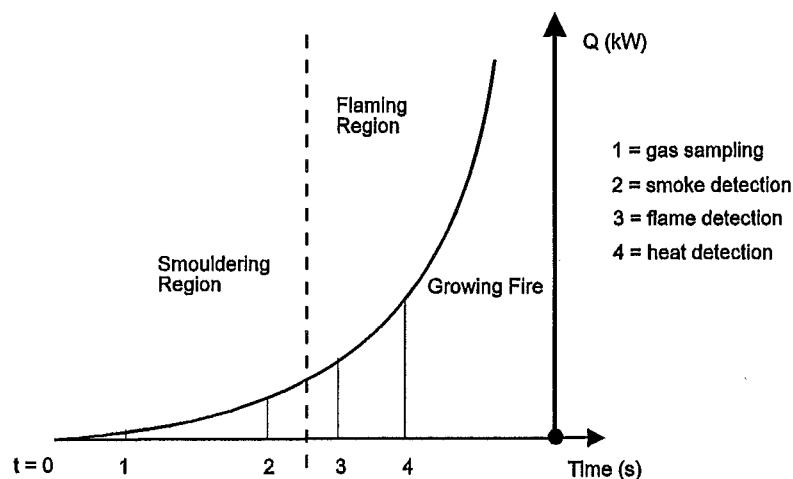


Fig. 7.1 : Relative comparison of detection times between types of detectors

### 7.2.2 Gas Sampling

These detectors sense gases produced by burning substances. The rapid response shown in Figure 7.1 is based on aspirators drawing sample air into a central analyser unit. Point type fire-gas detectors are usually located at the ceiling and have the same limitation as point type smoke or heat detectors, in that response time is dependant on the buoyancy and ceiling jet plumes driving the fire gases to the unit.

The gas sampling detection system is not common, and is intended for unusual environmental conditions such as extreme ambient temperatures and humidity, air velocity variations, vibration, and electrical interference. NFPA 72E [1990] provides design rules for selection, location and special considerations.

### 7.2.3 Smoke Detection

There are four common types of smoke detectors:

1. Ionisation point detector.
2. Photo electric point detector
3. Beam detector.
4. Aspirating smoke detector.

The point type detectors are affected by the time required for the smoke particles to be driven to the detector heads, as for gas sampling detectors. This problem of transport time lag and high ceilings as normally encountered in industrial buildings is discussed further in section 7.5.2.

Ionisation point detectors are suited to a flaming fire with smaller, drier smoke particles. These are more able to enter the ionisation chamber and disrupt the electrical sensing current. Photoelectric point detectors are suited to larger smoke particles from smouldering fires, due to their increased ability to diffract the light from the emission source.

Beam detectors operate on the same principle as the photoelectric point detector, except the emitter and receiver can be up to 100 m apart. This has the advantage of reducing the number of point detectors, plus allows the smoke detection to take place at a lesser height. This form of detection is very susceptible to obstructions, and is generally only used in open compartment areas. They should be suited to industrial occupancies except they are also susceptible to the following:

- vibrations; optical alignment must be stable ( $\pm \frac{1}{2}^\circ$ ).
- interference from industrial operations, and any birds or insects.
- false alarms from water vapour, refractive obstructions and dust clouds.

Aspirating detectors draw air into a sampling chamber where a photoelectric or similar light source illuminates any small particles present and the light is scattered onto a receiving cell. These systems are very sensitive due to the forced aspiration mechanism and the sampling technique. VESDA is the more common variety, and uses a Xenon tube as the illuminating source, and would be expected to have a response time similar to gas sampling detector systems.

#### 7.2.4 Flame Detection

Flame detectors respond to electromagnetic radiation in the ultraviolet (UV), visible and infra-red (IR) spectrums emitted from a burning flame [Wek, 1995]. UV flame detectors respond to a limited ultraviolet band of 185 to 260 nanometres, while IR detectors respond to a narrow band of infrared radiation centred at 4.35 micrometers. Flames produced by hydrocarbon fuels such as methane, petrol, oils and wood emit a large amount of IR radiation due to the emission band of CO<sub>2</sub>. Flame detectors are particularly suited to the protection of flammable liquids, due to the fast response characteristics required for rapid fire growth behaviour.

UV detectors provide the faster response and high sensitivity, whereas IR detectors are less susceptible to malfunctions due to contaminated optics, plus they can detect flames through dense smoke. Flame detectors are commonly used in industrial facilities such as hydrocarbon installations, aircraft hangars, and warehouses. They are suitable within large spaces but rely on line of sight and are not suitable for combustible products that are likely to smoulder extensively, such as within electrical installations and the bulk storage of raw products.

#### 7.2.5 Heat Detection

Heat detection is the most common form of detection, largely due to lower system costs. There are many types of heat detectors that all rely on the ability for the fire to drive convective heat currents past the detector element and trigger the element set point. The response time is dependant on the mass, area and specific heat of the detector element [Schifiliti, 1991]. This is reflected in the relationship for response time index (RTI):

$$RTI = \tau \cdot u^{1/2} \quad (m/s)^{1/2} \quad [7.1] \quad u = \text{gas velocity past detector (m/s)}$$

$$\tau = m \cdot c / h_c \cdot A_c \quad [7.2] \quad \begin{aligned} m &= \text{lumped mass of detector (kg)} \\ c &= \text{specific heat of element (kJ/kg} \cdot ^\circ\text{C)} \\ h_c &= \text{convective heat transfer co-eff.} \end{aligned}$$

- constant value ( $\text{kJ/m}^2\text{°C}$ )

$A_e$  = area of element being heated ( $\text{m}^2$ )

Typical values for RTI are  $30 (\text{m/s})^{1/2}$  for fast response elements, and  $190 (\text{m/s})^{1/2}$  for standard response [Buchanan, 1994]. The elements can also have different temperature ratings to vary the detection time. Incorporating the RTI value, the following relationship can be used to determine the response time of the detector, assuming no transport time lag (refer section 7.5.1):

$$t_r = \text{RTI} \cdot \ln [(T_g - T_a)/(T_g - T_r)] / u^{1/2} \quad (\text{s}) \quad [7.3]$$

$t_r$  = time for detector to respond (s)

$T_g$  = gas temperature (K)

$T_a$  = ambient temperature (K)

$T_r$  = rated temperature of detector (K)

The use of this lumped mass relationship may not be applicable for rate-of-rise heat detectors [Schifiliti, 1991].

Point type heat detectors can commonly use eutectic, bimetallic or liquid bulb elements, while linear detectors use nylon or thermoplastic materials. A larger fire is usually required to activate heat detectors in comparison to other detectors, although they generally require lower maintenance and are considered more reliable. Care needs to be taken when selecting temperature and RTI ratings to ensure they match the building environment (ie. high ambient temperatures) and the hazard.

### 7.3 ***Sprinkler Systems***

The most effective form of heat detection is the sprinkler because of the dual detection and fire fighting capabilities. As previously discussed, sprinklers are thought to be the only effective way of controlling an industrial fire. Sprinkler systems take many forms, but the basic principle is to automatically discharge water over a fire. The activation of a sprinkler system also provides a general alarm for evacuation, activation for ancillary fire safety devices, and signalling for the fire service.

#### 7.3.1 ***Piping Systems***

The usual type of sprinkler pipe system is a wet pipe system. The reticulation pipes are precharged with water and the sprinkler heads open once the quartzoid liquid bulbs expand and fracture under the heat of the fire. For cold environments antifreeze is used or the pipe network is gas pressurised and water is released into the pipes only when a sprinkler head activates.

Deluge systems are used in high hazard areas, such as aircraft hangars, to provide widespread coverage as soon as possible. For areas where there is a concern over false alarms, pre-action or double knocking systems are used. Water is only admitted into the pipework if a secondary detection system senses a fire condition, releasing a deluge valve.

### **7.3.2 Storage Protection**

The normal system to be used in an industrial application is the wet pipe system. For warehouse racking situations this may require pipework and heads within the racks. It is usually a compromise between greater head coverage and design water capacity from the roof only, or introducing sprinkler coverage into the racks and reducing the design density discharge. The different design requirements are clearly covered in design standards such as NZS 4541: Automatic Sprinkler Systems [SANZ, 1987].

The advantage with in-rack protection is activation of heads near to the seat of the fire. The disadvantage is the perceived restrictions on building operations. There is a continual fear that forklifts could accidentally break a head and cause disruptions and damage. Also, future flexibility is seen to be restricted once in-rack heads have been installed.

### **7.3.3 Types of Sprinkler Heads**

Roof mounted sprinkler heads have potential problems with activation delays due to gas transport and RTI time lags (refer sections 7.2.5 and 7.5.2). There are also problems with sprinkler water droplets reaching the seat of the fire. This may be caused by the concealment of the fire source, or the inability of the water droplets to penetrate past the hot fire plumes. Alternative solutions include the use of large drop sprinkler heads [Gibson, 1992]. These discharge 40% more water than normal 20 mm heads, creating larger and heavier drops that can penetrate the upward convective currents.

A recent development is the Early Suppression Fast Response (ESFR) sprinkler head. This has the ability to respond faster than other heads, while delivering large quantities of water per head. These systems are intended to suppress the fire rather than just control and do not require as many heads to operate when compared to a standard roof sprinkler system. The development has allowed increases in the limits for storage height and hazard classification for roof only protection. Within New Zealand approval of the ESFR systems is job specific and no general design standard is currently available.

### 7.3.4 Hazard Classification

The most difficult task in designing a sprinkler system is establishing the correct hazard classification. Once a sprinkler system is installed it becomes difficult to upgrade if storage heights increase or the industrial process involves a higher hazard. Questions that should be asked during the design stage are:

- What combustible products are intended to be stored or processed?
- Is there significant plastic encapsulation or containment to raise the classification?
- Is there any intention to increase storage heights or layouts in the future?
- Is there any intention to change the processing operation?
- Are other hazards present that may affect the design, such as environmental dangers, or storage/work areas that are particularly difficult to control?

Owners should complete storage declaration forms during the design to underline the liability the owner faces if these limits are exceeded.

### 7.4 Other Suppression Systems

Sprinklers are the most popular of active protection systems, largely due to the effectiveness of water as an extinguishing medium, its availability, and the relative cost compared to alternative systems.

Other suppression systems can be considered for special applications. Options include:

- Water mist: this is still in the developmental stage but has potential as an extinguishing agent for electrical, nautical and general applications. The advantages include less water requirements, greater heat absorption, and more effective smothering of the fire than conventional water systems.
- Foam : particularly effective for flammable liquid fires in smothering and cooling the fire source. Fire fighting foam can be introduced into sprinkler water supplies to combine the best qualities of the two systems, as detailed in NFPA 16, 1991 [Whiteley, 1993]. Foam monitors are sometimes used to supplement other fire protection systems, such as in an aircraft hangars and detailed in NFPA 409.
- Gas : Inert gas mixtures such as Inergen™, halocarbons such as FM 200™, and carbon dioxide systems can be used as alternative extinguishing mediums. They are impractical for large compartment areas such as industrial buildings due to the expense involved in

providing material for complete cover, and the difficulty in containing the discharged product.

- **Dry Chemical** : this system usually consists of compressed nitrogen cylinders that pressurise a large powder vessel, allowing dry powder to be discharged through fixed nozzles [Buchanan, 1994]. As for the gas systems, this form of fire protection is usually impractical for large open industrial buildings unless there is a target application. Dry chemical has the advantage of not dispersing once applied, assuming there are insignificant air currents.

Explosion protection requires different design techniques to fire suppression. A typical design should include compartmentation to segregate the explosion risk area, explosion relief vents to release pressure build-up of pressure, and a chemical suppressant such as CO<sub>2</sub> over the risk area linked to a rapid detection system. This should form part of an ongoing explosion risk control programme.

## **7.5 Design of Fire Protection Systems**

The design, installation, testing and maintenance of detection and suppression systems is provided by a range of design standards, including:

- NZS 4512 : Fire Alarm Systems
- NZS 4541 : Automatic Fire Sprinkler Systems
- NFPA 12 : Carbon Dioxide Extinguishing Systems
- NFPA 16 : Foam-Water Sprinkler and Spray Systems
- NFPA 17 : Dry Chemical Extinguishing Systems
- NFPA 69 : Explosion Prevention Systems
- NFPA 72E : Automatic Fire Detectors

The prescriptive sizing and spacing design requirements of these standards can be used, or specific system design can be undertaken to meet certain minimum performance criteria. For example, the sprinkler design standard places design water density discharge and pressure requirements, and through applying hydraulic design techniques the pipework network and sprinkler head detail can be established.

### **7.5.1 Detection Times**

Often the inclusion of either detection or suppression systems is used to validate the overall fire safety strategy for the building. An argument can be used that has the detection/suppression equipment activating at a certain time during the design



fire, resulting in effective evacuation and fire control. The key variable in this equation is the time to detection -  $t_d$ .

Variables that effect  $t_d$  include:

- a) fire growth rate and maximum heat release rate.
- b) ceiling height.
- c) separation distances between detectors.
- d) detector type and setting.
- e) obstacles and venting.
- f) fire plume and ceiling jet.

The time to detection is often miscalculated as only being the response time of the detector assuming steady state gas flow behaviour, and utilising the detectors known RTI and activation temperature. In reality detectors are expected to activate during the growth stages of the fire, and not the steady state phase. Consideration should therefore be given for the transport time lag, or the delay for fire gases to travel up to the ceiling and across to the detector. Obviously in a high compartment such as a single storey industrial building, this time will be significant.

### 7.5.2 Transport Time Lag

Mowrer [1990] highlighted that the DETACT-QS program in FPETOOL and FIRECALC does not allow for a transport time lag. In a growing fire the heat release rate being sensed at a detector can lag the actual heat release rate by a significant margin. This difference continues to grow as long as the fire continues to grow. Newman [Mowrer, 1990] provided an expression that calculates this time delay based on a  $t^2$  growth fire:

$$t_l = (1.4 r + 0.2 H) / (A_k \alpha_t H)^{1/5} \quad [7.4]$$

$t_l$  = transport time lag (s)

$r$  = radial distance from fire axis to detector (m)

$H$  = height above plume source (m)

$A_k = g / (c \rho_o T_o)$

= 0.028 m<sup>2</sup>/kg

$\alpha_t$  = power law growth co-efficient (kW/s<sup>2</sup>)

**Example:** Calculate the transport time lag and total detection time for a heat detector rated at 57 °C and 30 (m/s)<sup>1/2</sup> RTI, located on a 10 m ceiling and at the following radial distances away from the fire axis:

- a)  $r = 3$  m
- b)  $r = 10$  m

Fire growth rate is medium,  $\alpha_t = 0.01172 \text{ kW/s}^2$ .

$$\text{a) } r = 3 \text{ m : } t_l = (1.4 \times 3 + 0.2 \times 10) / (0.028 \times 0.01172 \times 10)^{1/5} \\ = 19.5 \text{ s}$$

$$\text{from FPETOOL DETACT : } t_r = 391 \text{ s} \\ \therefore t_d = 410 \text{ s}$$

$$\text{calculating HRR @ } t_r (391 \text{ s}) = \alpha_t \cdot t_r^2 \\ = 1792 \text{ kW}$$

$$\text{@ } t_d (410 \text{ s}) = \alpha_t \cdot t_d^2 \\ = 1970 \text{ kW}$$

$$\text{b) } r = 10 \text{ m : } t_l = (1.4 \times 10 + 0.2 \times 10) / (0.028 \times 0.01172 \times 10)^{1/5} \\ = 50.2 \text{ s}$$

$$\text{from FPETOOL DETACT : } t_r = 721 \text{ s} \\ \therefore t_d = 771 \text{ s}$$

$$\text{calculating HRR @ } t_r (721 \text{ s}) = \alpha_t \cdot t_r^2 \\ = 6093 \text{ kW}$$

$$\text{@ } t_d (771 \text{ s}) = \alpha_t \cdot t_d^2 \\ = 6971 \text{ kW}$$

This example shows that the heat release rate (HRR) can be significantly different based on the  $t_l$ . For instance the second example indicates that the HRR at the response ( $t_r$ ) time of 721s is 6093 kW, whereas the actual heat release rate based on the detection time ( $t_d$ ) of 771s is 6971 kW. This is a 14% difference where the underestimation of HRR could affect the life safety design or the ability of the suppression to control the fire.

It should be noted that DETACT-QS has other limitations to only considering steady state fire conditions. The program also assumes [Deal, 1994]:

1. unconfined ceiling profile.
2. flaming fire.
3. flame height is not a factor.
4. detectors are fixed temperature devices.
5. detectors are exposed to the maximum ceiling jet velocity and temperature.

### 7.5.3 Smoke Detectors

The response of smoke detectors can be approximated using the same method as applied for heat detectors. The following parameters are usually used for inputting into DETACT [FPETOOL, 1994]:

- $RTI = 0.005 \text{ (m/s)}^{1/2}$ , or as close to 0 as possible.
- $\Delta T = 13 \text{ }^{\circ}\text{C}$  between ambient and detector activation temperature.

The temperature difference approximation is based on the theory that the concentration of particles to which the detector responds is proportional to the temperature rise of the fire gases. The adoption of  $13 \text{ }^{\circ}\text{C}$  as the reference temperature rise is based on a most likely outcome from limited experimental tests [Heskestad, 1991].

### 7.6 Ancillary Systems

The activation of a detection system should not only result in the sounding of alarms, but also the activation of ancillary fire protection devices. This signalling is through a central alarm control panel, with possible ancillary control actions being:

- Fire service notification.
- Smoke extract and management systems.
- Remote indicator panels.
- Security over-rides.
- Plant shut-down.
- Release of magnetic door holders, and closing of fire and smoke-stop doors.
- Emergency lighting.
- Activation of special suppression systems.
- Return of lifts (if any) to the ground floor.

Figure 8.5 shows a typical interactive system. The ability to complement fire safety features to maximise the potential protection of a building forms a key part of the complete fire safety strategy.

### 7.7 Conclusions

1. System goals for a site fire safety strategy can be placed in three categories: life safety, property protection, and business protection.

2. To determine the most effective fire safety strategy in terms of cost and performance, a site fire risk assessment should be completed as part of the design process.
3. The minimum level of fire protection expected for a single storey industrial building is a manual call point and alarm system, for life safety purposes. Inclusion of automatic detection or suppression systems enhances life safety, and should be incorporated in building design wherever possible.
4. Fire safety designs relying on detector performance, must account for the detector RTI, activation temperature, and the transport time lag.
5. Activation of detection systems should not only sound alarms, but also initiate ancillary devices such as remote indicator panels, fire service attendance, and smoke management systems.
6. Sprinklers are the only expected method of controlling a fire within a typical industrial complex. The fire service can not be expected to attack and suppress a fire from receiving an alarm call without sprinkler support.
7. A critical part of sprinkler design is establishing the correct hazard classification. This evaluation should form part of the initial site risk assessment.

## 8.0 ROOF VENTING

### 8.1 *Objective*

This section aims to provide a design method for the sizing and operation of either natural or mechanically operated roof vents in industrial buildings. The discussion emphasises that smoke control forms only part of an overall fire design strategy, and can not be treated as the sole solution to effective fire management.

The question of whether roof vents should be included in a sprinklered environment is also addressed. This section concludes that the two fire control systems should be integrated where possible, with careful attention given to their combined operation.

### 8.2 *Introduction*

A developing fire in an industrial building results in buoyant, hot gases rising vertically from the combustion zone and then flowing horizontally below the roof until blocked by a vertical barrier (a wall or draft curtain). This initiates the formation of a deepening hot layer of gases below the roof.

If this process continues, the deepening smoke layer radiates heat to unburnt combustible surfaces until a minimum radiation intensity causes spontaneous ignition. This is known as flashover, and results in a fully involved fire. Flashover is expected to occur when the hot upper layer temperature exceeds 600°C, or radiative heat flux from the hot upper layer to combustible items exceeds 20 kW/m<sup>2</sup>.

#### ***Benefits of Venting***

Avoiding a flashover condition should be an objective in the design of single storey industrial buildings with high fire loads. Venting the upper smoke layer from the compartment is not expected to prevent flashover, but it is expected to delay the event.

Venting not only releases convective heat to outside, but also provides the following advantages:

- facilitates a safe means of escape
- aids fire fighters in accessing the seat of the fire.
- reduces property and contents damage due to smoke and hot gases.
- lowers the risk of explosion due to build-up of unburnt gases.
- limits the number of sprinklers activating (if present).
- allows purging of smoke after the fire is under control.

Avoiding a flashover condition or controlling the smoke behaviour does not guarantee that the fire will not spread throughout the compartment. A developing

fire has the ability to spread by direct radiation or flame transfer. If it is apparent that a fire would engulf the whole building, then it must be accepted that a smoke control system will only be effective during the early stages of a fire.

Hansell [1993] considers that flashover is likely to occur in high rack storage areas, regardless of the presence of smoke extraction. This is based on the theory that storage products are very close to, or within, the upper smoke layer. He considers sprinklers to be essential for effective property protection in this circumstance.

### ***Fire Design Strategy***

A roof venting system should form **part** of a fire safety design strategy, depending on the fire safety objectives. Careful consideration is needed to determine the best combination of fire safety options for the level of risk and acceptable fire outcome. This could result in a timber warehouse being protected by automatic detectors, sprinklers and roof vents. Section 7.0 discusses this selection process further, and outlines the method for developing a fire design strategy.

This Section concentrates on the use of roof vents. It presents methods for calculating smoke production rates for design fires, and then designing vents to suit. A number of related issues are also discussed, including:

- design differences between natural venting and mechanical venting
- venting limitations for growing fires
- providing replacement air
- the use of smoke curtains
- controlling the operation of vents
- interaction of roof vents and sprinklers

A worked example at the end of this chapter demonstrates the use of the calculation methods.

## **8.3 Smoke Development**

To control the heat and smoke within a compartment, there first must be an understanding of the design fire and the constraining features of the affected building (ie. compartment size, vent locations etc.).

For a large space smoke generated from a fire is expected to rise up underneath the roof, and then spread radially outwards as a ceiling jet. Between 60 % and 90 % of the fires heat output is transferred to this smoke layer [Pagella and Faveri, 1993]. The resulting depth of smoke becomes a function of:

- type of burning product (ie. plastics versus wood products).
- fire growth and rate of smoke generation.
- area of reservoir beneath the roof - external walls or smoke curtains may define the reservoir boundaries.
- presence and effect of sprinklers and smoke vents.

The driving mechanism for the smoke is the release of convective heat currents and hot volatile vapours. The difference in densities between the ambient air and the hot gases results in an upward movement, with surrounding air becoming entrained into the vertical smoke plume.

Two methods are available to estimate the rate of smoke production. The first is limited to fires in the early growth stages, and is dependant on the fire dimensions, smoke clearance heights and smoke temperature. The second method is based on heat output and smoke clearance heights, and has a modified form to account for large fires.

### 8.3.1 Smoke Clearance Heights

A key component in these formulae is the “smoke clearance height” ( $y$ ), which is the distance from the floor to the underside of the hot smoky upper layer. This can be determined in an iterative process involving the following variables:

- 1) fire initiation, assuming the smoke clearance height to be the ceiling height.
- 2) the compartment filling with smoke as the fire continues to grow. The smoke clearance height reduces as this smoke layer deepens. This increases the rate of smoke production and smoke temperature.
- 3) the effects of smoke extraction through venting systems. This increases the smoke clearance height.

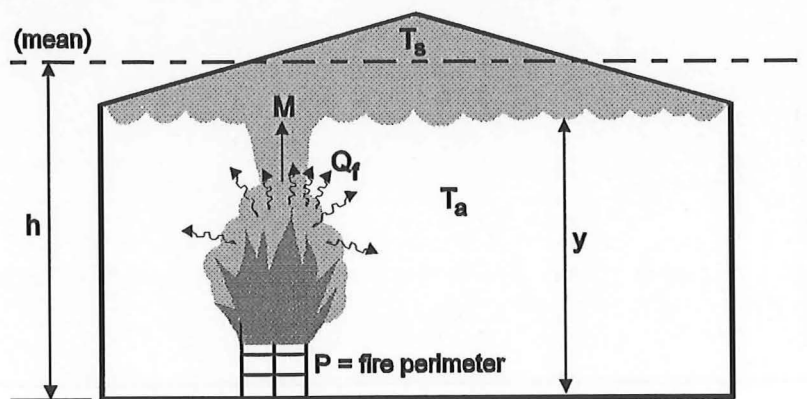


Fig. 8.1 : Nomenclature Used for Developing Fires

NFPA 92B provides formulae to determine the smoke clearance height at any time in an *unvented* space. These formulae depend on whether the fire is steady state or non-steady state, and assume an axisymmetric plume:

- 1) Steady State:

$$y/h = 1.11 - 0.28 \ln [(t Q_f^{1/3} / h^{4/3}) / (A/h^2)] \quad [8.1]$$

## 2) Non-Steady State:

$$y/h = 0.91 [t/(t_s^{2/5} h^{4/5} (A/h^2)^{3/5})]^{-1.45} \quad [8.2]$$

$h$  = height of compartment (m)

$t$  = time from fire initiation (s)

$Q_f$  = heat output of fire (kW)

$A$  = area of compartment (m<sup>2</sup>)

$t_s$  = time at which the heat output is  
1.055 MW (s)

An alternative to undertaking this manual exercise, is to use a computer based fire simulation programme such as FPETOOL or CFAST. These programmes can give smoke clearance heights as a function of time for a given fire scenario taking into account all the above variables (also refer Section 5). If an extract system is operating, the smoke clearance height will be affected by the performance of both the extract system and the smoke generation rate. The results from the above relationships need to be placed into a spreadsheet and adjusted to account for:

- when the extraction system begins operation
- the rate of extraction

This becomes an iterative process involving the mass flow rate equations given in Sections 8.3.3 and 8.3.4. The success of the extraction system is usually based on keeping the smoke above a minimum height for the design period.

This minimum height may be influenced by the need to keep the design fire below a minimum heat output value. A formula is given in NFPA 204M that determines the heat output before gas temperatures exceed 540°C. Exceeding this value may either result in flashover or failure of unprotected steelwork. The formula is based on curtained compartments where the curtain depth exceeds 20% of the ceiling height:

$$Q_{\max} = 1.3 \times 10^3 y^{5/2} \quad (\text{kW}) \quad [8.3]$$

$Q_{\max}$  = maximum heat output of fire before  
the gas temperature exceeds 540°C

### 8.3.2 Smoke Temperatures

Two forms of smoke temperature are referred to in the text:

- Smoke plume temperature
- Upper layer smoke temperature

The notation is the same (  $\Delta T_{s-a}$ ,  $T_s$  ), but the difference is given in the key reference alongside each formula.



The temperature of the smoke plume can be estimated by the following relationship [Hinkley, 1992]:

$$\Delta T_{s-a} = Q_c / M C_p \quad (^\circ\text{C}) \quad [8.4]$$

$\Delta T_{s-a}$  = smoke plume temperature above ambient ( $^\circ\text{C}$ )

$Q_c$  = convective output of fire (kW)

$C_p$  = specific heat of air at constant pressure (kJ/kg K).

$M$  = smoke production rate (kg/s)

The upper layer smoke temperature can either be determined through using ASETBX in the FIRECALC suite of fire design procedures, or applying the compartment temperature relationship established by Foote, Pagni and Alvares [Walton and Thomas, 1992]. The ASETBX routine applies to non-vented compartments, while the Foote et al procedure applies to forced ventilation fires.:

$$\frac{\Delta T_{s-a}}{T_a} = 0.63 \left[ \frac{Q_f}{M_F C_p T_a} \right]^{0.72} \left[ \frac{h_k A_T}{M_F C_p} \right]^{-0.36} \quad [8.5]$$

$\Delta T_{s-a}$  = Smoke layer temp. above ambient (K)

$T_a$  = Ambient temp. (K)

$Q_f$  = Heat output of fire (kW)

$M_F$  = Mass flow from fan (kg/s)

$h_k$  = Heat transfer coefficient (kW/m<sup>2</sup> K)

$A_T$  = Total area of compartment enclosing surfaces (m<sup>2</sup>).

### 8.3.3 Method 1 : Mass Flow Rate Based on Fire Size

Compared with the total volume of air entrained by the fire, the volume of the fuel gases and unburnt decomposition matter is relatively small. One method to determine the rate of smoke production is therefore based on the rate of air entrainment. This rate is dependant on the perimeter of the fire, the heat output and the effective height of the column of gases. It also assumes that there is no restriction on the supply of air, and that the fire is fuel controlled. The following relationship estimates the rate of air entrainment [Butcher and Parnell, 1979]:

$$M = 0.096 P \rho_o y^{3/2} (g T_a / T_s)^{1/2} \quad (\text{kg/s}) \quad [8.6]$$

$P$  = Perimeter of fire (m)

$y$  = Smoke clearance height (m)

$\rho_o$  = Density of ambient air (kg/m<sup>3</sup>)

$T_a$  = Absolute temperature of ambient air (K).

$T_s$  = Absolute temperature of smoke plume (K).

Based on standard air at 17°C, and  $T_s = 1100$  K, the expression for smoke production reduces to:

$$M = 0.188 P y^{3/2} \quad [8.7]$$

This relationship shows clearly that the rate of smoke production is directly proportional to the size of the fire (P) and dependant upon the smoke clearance height (y) above it.

Fire size (P) can be adequately predicted using three cases:

- 1) during the early growth stages of a fire, or
- 2) where sprinklers are present, or
- 3) if the fire source is constrained (ie. a pool fire).

The Smoke Ventilation Association (1990) tabulates recommended maximum fire sizes for designing smoke ventilation systems, and states that fire sizes above these values should not be considered. This is a prescriptive approach, and may be relevant for controlled fires, such as with sprinkler operation and pool fires. For a sprinkler controlled fire, the fire size is set on a 3m × 3m square, or 12m perimeter for an occupancy with a medium fire load (500 - 1500 MJ/m<sup>2</sup>) [Butcher and Parnell, 1979]. The NZ Building Code states that a 12m perimeter fire has a heat output of 5 MW [BIA, 1991].

For uncontrolled fires the maximum size of the fire should be based on the time needed to achieve the fire safety objectives. This may be based on when flashover is expected to occur, or the minimum time for safe evacuation. The need to develop a fire design strategy is discussed further in Section 7.1.

#### 8.3.4 Method 2 : Mass Flow Rate Based on Heat Output

NFPA 204M provides formulae that are not based on fire size, but on heat output. For fires with high heat outputs, it is considered that the use of the fire size formulae gives mass flow rates that are too low [Hinkley, 1992]. The NFPA 204M formulae, as initially proposed by Heskestad [Pagella and De Faveri, 1993], define a small and large fire based on a critical heat output.

$$Q_{crit} = 2.3 \times 10^5 y^{5/2} \quad (W) \quad \begin{array}{l} \text{Small Fire: } Q_c < Q_{crit} \\ \text{Large Fire: } Q_c > Q_{crit} \end{array} \quad [8.8]$$

The mass flow rates are determined by the following formulae:

$$\text{Small Fire: } M = 7.1 \times 10^{-3} Q_c^{1/3} [y^{5/3} + 2.6 \times 10^{-4} Q_c^{2/3}] \quad (kg/s) \quad [8.9]$$

Large Fire:  $M = 5.3 \times 10^{-4} y Q_c^{3/5} \text{ (kg/s)}$  [8.10]

$Q_c$  = Convective heat output of fire (W)

$y$  = Smoke clearance height (m)

The conversion of the mass rate of production of smoke to a volume rate can be made by dividing by the density appropriate to the smoke temperature (also refer Section 8.4.2). An expression for density is:

$$\rho_T = 1.22 \times \left[ \frac{290}{T_s} \right] \text{ kg/m}^3 \quad [\text{Based on } T_a = 290 \text{ K}] \quad [8.11]$$

$\rho_T$  = Density of air at temperature T (kg/m<sup>3</sup>)

$T_s$  = Absolute temperature of smoke plume (K)

## 8.4 Roof Vents

A roof ventilation system is intended to expel smoke so as to provide the following advantages [Hansell, 1993]:

- facilitate safe means of escape.
- aid fire fighters in accessing the seat of the fire.
- reduce damage due to smoke and hot gases (if the fire can be controlled)
- lower the risk of total roof collapse.
- lower the risk of flashover by reduction of compartment temperatures.
- lower the risk of explosion due to build-up of unburnt gases.
- limit the number of sprinklers activating.
- allow purging of smoke from a building after the fire is under control.

If the venting system is adequately sized, it will expel smoke at the same rate that is being produced by the fire. The usual design criterion is to maintain a 2.5m high clear zone from the floor, primarily for the limiting the effects of smoke on evacuees and firefighters. The Smoke Ventilation Association (1990) also recommend that a clear layer of 500 mm is kept above stacked goods if spontaneous ignition is considered a risk.

Key design parameters are the expected fire growth and steady state conditions, plus the smoke development rates. It should be noted that vents do not draw smoke through their openings, rather the buoyancy of the hot smoke provides the driving force (refer equation [8.24]). If the extraction rate exceeds the mass flow rate attributable to the buoyancy force then cool air is drawn from the lower layer.

Roof venting can be provided by natural vents or mechanical extraction. Skylights can also be expected to perform as roof vents, but only at elevated temperatures. For example 'Durolite', a common skylight product and manufactured by Dimond Industries, has a decomposition temperature of 350°C. Systems that are designed

specifically for venting are usually automatically controlled through detectors or fusible links, so as to begin operation at much lower temperatures.

The following sections provide calculation techniques for natural and mechanical venting systems, and discuss associated issues such as vent control and replacement air. The methods for sizing vents however rely on this clear knowledge of the system's maximum expected operating condition.

#### 8.4.1 Natural Ventilation

The required vent area is calculated by equating the mass rate of flow through vents with the mass rate of smoke production [Hinkley, 1992]. The following equation is based on a 'large' fire with the smoke production being dependant on fire size:

$$A_v = 0.13 P y^{3/2} / (h-y)^{1/2} \quad (\text{m}^2) \quad [8.12]$$

NFPA 204M gives an equivalent equation based on heat output, for small fires ( $Q_c < Q_{\text{crit}}$ ):

$$A_v = 2.7 \times 10^{-3} Q_c^{1/3} [y^{5/3} + 2.6 \times 10^{-4} Q_c^{2/3}] / (h-y)^{1/2} \quad (\text{m}^2) \quad [8.13]$$

For 'large' fires where  $Q_c > 0.2 Q_{\text{crit}}$  (ie. there is some overlap with small fires):

$$A_v = 1.94 \times 10^{-4} Q_c^{3/5} y / d^{1/2} \quad (\text{m}^2) \quad [8.14]$$

$Q_f$  = Convective heat output of fire (W)

#### ***Vent Area for Growing Fires***

NFPA 204M [Hinkley, 1992] provides a design method for growing fires, based on achieving an 'intervention' time. This is the time in which the venting system is expected to remain effective, and again is related to the fire design strategy. The formula assumes a square law increase in heat output with time, and does not account for a steady state condition. For this reason it should only be used for *growing* fires.

$$A_v = [0.81 [(t_d + t_i) / t_s]^{6/5} y] / (h-y)^{1/2} \quad (\text{m}^2) \quad [8.15]$$

$t_d$  = vent 'detection' time (s)

$t_i$  = 'intervention' (or design)  
time (s)

$t_s$  = time at which the heat  
output is 1.055 MW (s)  
[refer section 5.3]

Figure 8.2 shows a range of typical fire growth curves, and overlays events as a function of time during a fire.

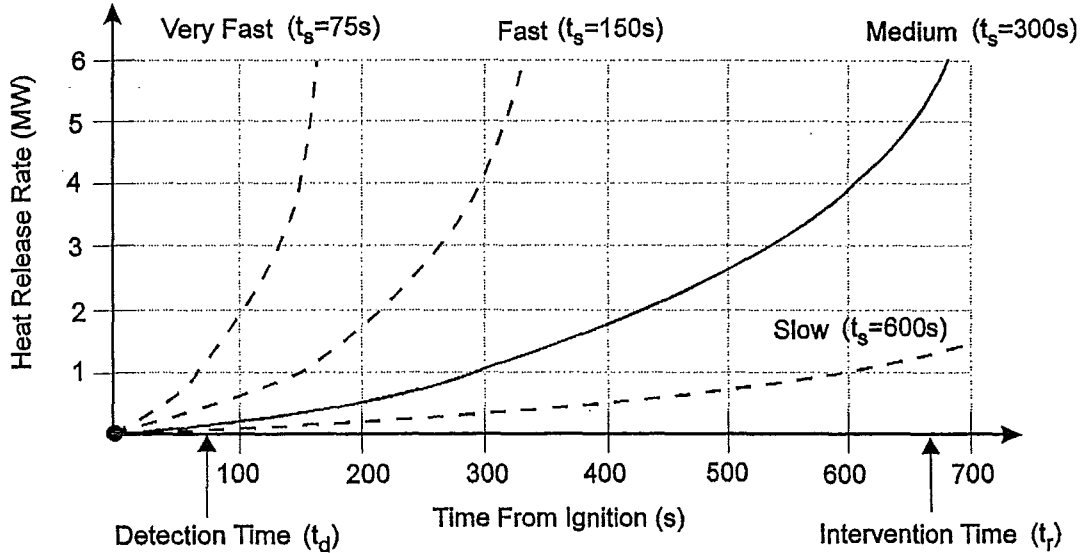


Fig. 8.2 : Fire Growth Curves

NFPA 204M provides a quick reference table that relates fire growth, design time, ceiling height and vent spacing. Factors are included that compensate for design parameters outside the listed values.

### Maximum Vent Size

There is a maximum vent size that ensures air from beneath the layer of hot gases is not drawn into the vents. This is related to a maximum rate of extract that depends on the Froude number,  $F_C$ , and must not exceed a critical value determined by [Hinkley, 1992]:

$$F_C = V_v / [(g \Delta T_{s-a} / T_a)^{1/2} (h-y)^{5/2}] \quad [8.16]$$

$V_v$  = volume rate of flow  
through a single orifice.

Accepted working figures for  $F_C$  are:

1. Vents near the side of a smoke reservoir:  $F_C = 2.0$
2. Vents near the center of a smoke reservoir:  $F_C = 2.5$

The critical vent size is determined from the following relationship:

$$(A_v)_{crit} = 0.707 F_C (h-y)^2 / C_d \quad [8.17]$$

$C_d$  = coefficient of discharge  
(usually taken as 0.6).

For a vent near the center of a reservoir, this simplifies to:

$$(A_v)_{crit} = 2.94 (h-y)^2 \quad [8.18]$$

Note that the recommended maximum spacing for natural vents is 20 m apart [Smoke Ventilation Association, 1990]. NFPA 204M requires that on a plan view of the building, the distance between any point on the floor and the nearest vent does not exceed 2.8 x (building) height.

#### 8.4.2 Mechanical Extraction

The general design of a mechanical system is similar to that of a natural venting system. Care is required with determining the duty and number of fans required. The mass flow extraction rate will vary according to smoke layer temperature. Based on a known compartment temperature, the volumetric exhaust rate is [Hansell and Morgan, 1994]:

$$V_F = \frac{M T_s}{\rho_o T_a} \quad [8.19]$$

$V_F$  = volumetric exhaust rate ( $m^3/s$ )  
 $T_s$  = smoke layer temperature (K)  
 $M$  = smoke production rate (kg/s)  
 $T_a$  = ambient air temperature (K)

#### *Number of Extraction Outlets*

To avoid drawing air from beneath the smoke layer, and creating a 'plug holing' effect, a minimum number of extraction outlets are required. This is similar to providing a minimum vent size for natural ventilation. The critical exhaust rate is based on the following equation [Hansell and Morgan, 1994]:

$$M_{crit} = \beta (g d^5 T_a \Delta T_{s-a} / T_s^2)^{1/2} \quad (kg/s) \quad [8.20]$$

[ $\beta$  = coefficient: 1.3 for a vent near a wall; 1.8 for a central vent]

The required number of extract vents (N) is then given by:

$$N \geq \frac{M}{M_{crit}} \quad [8.21]$$

### ***Effects from Temperature Variations***

Fan performance can be affected by changes in compartment temperature:

1. Increase in Temperature: given that the mass flow rate of smoke remains constant, an increase in upper layer temperature would increase the volume rate of smoke required to be extracted by the fan(s). Unless the speed or performance of the fan(s) can also be increased, the smoke layer will deepen and exacerbate the problem.
2. Decrease in Temperature: The critical exhaust rate is expected to decrease, based on the equation given above for  $M_{crit}$ . Reduction in the critical exhaust rate indicates that either the number of vents should be increased, or the designed system will draw air from below the smoke layer.

#### **8.4.3 Pressure Effects**

Venting systems can be ineffective if the smoke buoyancy pressure is overcome by inlet and wind pressures.

##### ***Inlet Pressure***

The 'inlet' pressure drop takes two forms, depending on whether it is natural or mechanical venting being considered. For natural ventilation Hinkley provides a formula that accounts for pressure rise due to constraints on expansion. This is only of any significance if both the ratio of inlet area to compartment area is very small (est. < 0.01%) and the rate of rise of temperature in the compartment is nominally greater than  $2 \text{ K/s}^{-1}$ . If a natural vent system is sized correctly this factor can usually be ignored.

For mechanical venting systems, there is a pressure drop across the inlet into the extract fan. This is a function of mass flow rate, coefficient of discharge, inlet area and temperatures. The coefficient of discharge can vary according to the inlet profile, and is usually taken as 0.6 for standard systems. The equation provided by Hinkley [1992] is:

$$P_I = \left[ \frac{M}{C_d A} \right]^2 \frac{(T_a + \Delta T_{s-a})}{(2T_a \rho_o)} \quad (\text{Pa}) \quad [8.22]$$

$P_I$  = pressure drop across fan inlet (Pa)

$M$  = Smoke flow rate ( $\text{kg/s}$ )

$C_d$  = coefficient of discharge (usually taken as 0.6)

$A_I$  = area of opening ( $\text{m}^2$ )

$\Delta T_{s-a}$  = smoke layer temperature above ambient (K)

### **Wind Pressure**

Wind pressures can have a marked effect on the ability for smoke to ventilate. The following equation gives the wind pressure resulting from wind velocity [Hinkley, 1992]:

$$P_W = C_P \rho_o (V_W)^2 / 2 \quad (\text{Pa}) \quad [8.23]$$

$P_W$  = pressure increase due to wind above the undistributed free wind stream (Pa).

$C_P$  = pressure coefficient (typically -0.8 for a flat roof, but + ve for the windward side of pitched roofs).

$V_W$  = velocity of free wind stream (m/s).

For industrial buildings the roof pitch is usually low, and the preferred location of vents is on the roof. This means that any wind will aid smoke venting due to the probable negative (suction) pressure. Attention needs to be given as to where the smoke is likely to go in a prevailing wind. There should be no possibility of smoke re-entering the building.

### **Buoyancy Pressure**

The buoyancy pressure is the driving force for smoke movement, and can be expressed [Hinkley, 1992]:

$$P_B = g \rho_o \Delta T_{s-a} d / (T_a + \theta) \quad [8.24]$$

$P_B$  = buoyancy pressure (Pa)

$d$  = depth of smoke layer (m)

$T_a$  = absolute ambient temperature (K)

$\Delta T_{s-a}$  =  $(T - T_a)$  temperature of smoke above ambient

$\theta$  = temp of gases above ambient (K)

### **Combining Pressures**

The following equation equates the contributing pressures [Hinkley, 1992]:

$$P_R = (P_B - P_W - P_I) \quad (\text{Pa}) \quad [8.25]$$

$P_R$  = resultant pressure

$P_B$  = buoyancy pressure

$P_W$  = anticipated maximum adverse wind pressure



$P_I$  = pressure drop across inlet

If the vent system can not overcome constraining pressure forces the smoke layer will drop, resulting in an increase in buoyancy pressure. This assists in driving the gases out of the vents. A venting system becomes ineffective if the smoke layer falls below the minimum allowable height in the fire design. Options available to overcome this are:

- alterations to the building design to minimise the effect of the external pressures.
- increase the vent sizes to reduce inlet pressures.
- increase the performance of the mechanical extract fans.

#### 8.4.4 Replacement Air

An important feature in an effective smoke ventilation system is replacement air (or 'make-up' air). Ideally, replacement air should be introduced at low level from all directions, and at low velocity (recommended maximum velocity is 5 m/sec [Buchanan, 1994]). High level intakes can be used if smoke curtains or screens have been fitted, although care has to be taken to avoid turbulence of the smoke.

The quantity of replacement air needs to match the maximum extract volume, with consideration for the change in air densities at elevated temperatures. The location of the inlets need to allow for the effects of the wind. Ideally, inlets should be evenly distributed around the building, plus there should be no risk of smoke recirculating back into the building through inlets.

The ratio of inlet and outlet vent areas, can greatly affect the *effective* outlet area [Hinkley, 1992]. If the capacity of the venting system is to be within 90% of its computed value, then this inlet and outlet vent ratio must be unity if the layer of hot gases has a temperature of 800°C above ambient. If the layer is anticipated to be at a low temperature, then the ratio must be over 2. The effective vent area is determined by the following formula:

$$1/A_v^{*2} = (1/A_v^2) + (1/A_I^2)[T_o / (T_o + \theta)] \quad [8.26]$$

$A_v^*$  = effective area of  
outlet vents ( $m^2$ ).  
 $A_I$  = area of inlets ( $m^2$ )  
 $T_o$  = ambient temp. (K)  
 $\theta$  = upper layer temp (K)

Refer Sections 8.4.3 for determination of the pressure drop across inlets, and the effect this has on the performance on the extraction system.

### 8.4.5 Vent Control

The method of control for a smoke extract system is critical to its success. The opening of natural ventilators can either occur through operation of an automatic fire alarm signal, or through a fusible link. The former method would usually provide the quicker response in an emergency.

Latching mechanisms need to be jam-proof, corrosion resistant, and resistant to pressure differentials arising from windstorms, process operations, overhead doors, or traffic vibrations.

Mechanical systems are usually started by a fire alarm signal or manual operation. Again an automatic signal is the most effective, especially during unmanned periods. The recommended form of automatic detection is zoned smoke detectors; they are expected to provide the quickest response to a fire. Figure 8.3 shows a typical schematic diagram for the interfacing of automatic alarms and mechanical systems.

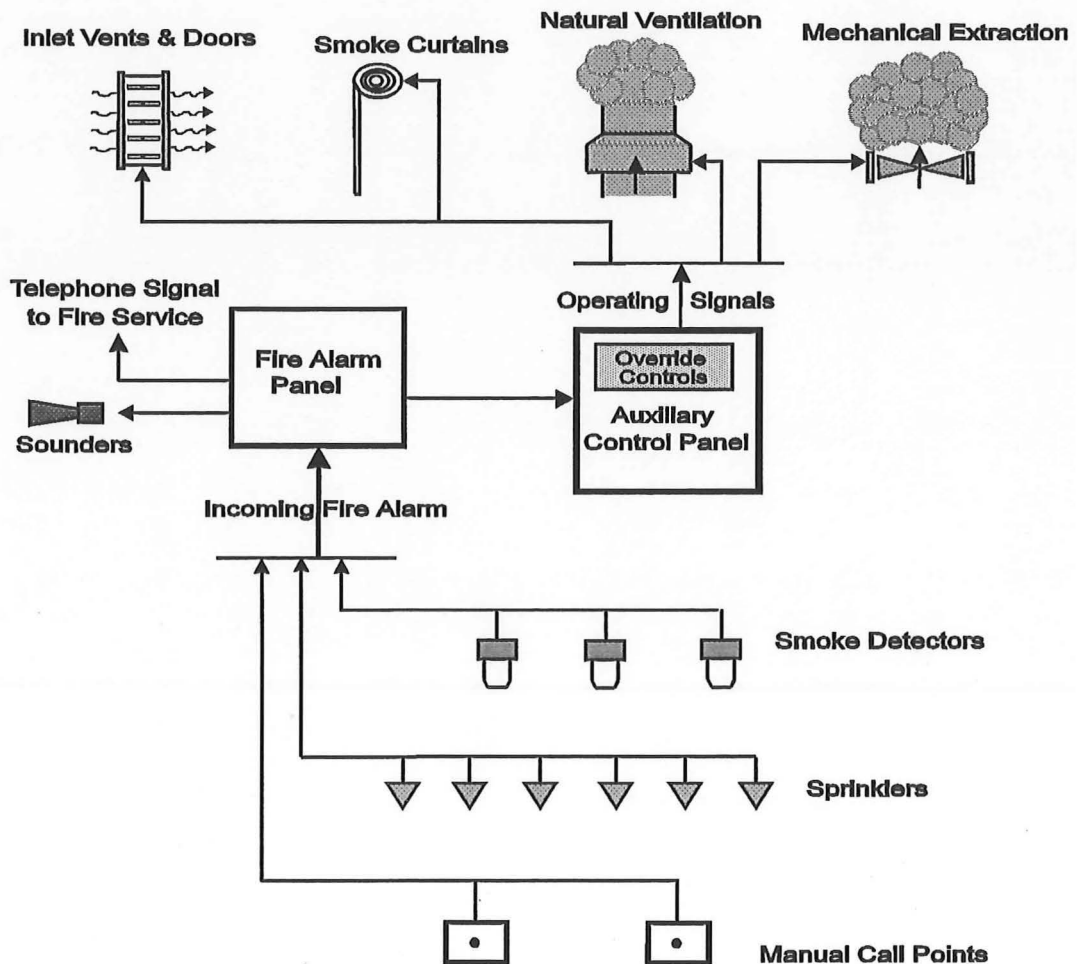


Fig. 8.3 : Schematic Diagram for Typical Fire Alarm and Control System

The control requirement stipulated in the Building Code of Australia 1990 for smoke extract fans is [Buchanan, 1994]:

“All smoke extract fans must start sequentially and be activated by the operation in the area served by the fan of:

- a) a sprinkler system
- b) a fire detection and alarm system complying with NZS 4512
- c) a detector system comprising -
  - i) smoke detectors spaced not more than 30 m apart and 15 m from any draught curtain, bulkhead or wall and not less than one detector for each 500 m<sup>2</sup> of floor area; or
  - ii) rate of rise detectors spaced not more than 15 m apart and 7.5 m from any draught curtain, bulkhead or wall and with not less than one detector for each 250 m<sup>2</sup> of floor area; and
  - iii) not less than 2 detectors located on opposite sides of each fan inlet.”

The NZ Building Code Acceptable Solutions also include the following features for mechanical extraction systems:

- manual control available for operation by the Fire Service
- independent control and power systems protected by the effects of fire for at least 60 minutes.
- fan system rated for a maximum operating temperature of 200°C, and continuous operation in a temperature of 40 °C for no less than 60 minutes.

An extraction system relies on replacement air and these systems need to interact with the vent controls. A common method is to open automatic doors or motorised wall vents through a signal at the alarm panel. If replacement air is provided through the roof, zoning of roof units, fire detectors and smoke curtains may be required. The design of powered system controls should always ensure a fail safe condition, resulting in the fans operating and natural ventilators being in the open position

## **8.5 Worked Example - Roof Venting Design**

The same warehouse as described in Section 5.4 is required to have either natural or mechanical roof venting to limit smoke layer height to avoid flashover, assuming one rack of goods becomes fully involved in a fire. The layout and characteristics of the fuel are as follows; the only difference to the example in Section 5.4 is the deletion of roof skylights:

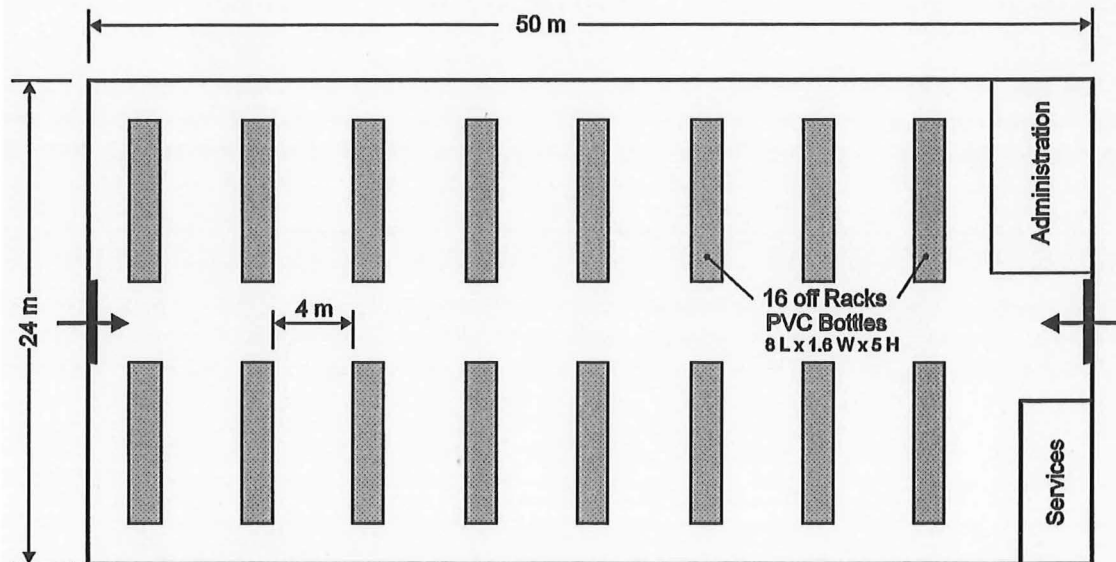


Fig. 8.4 : Warehouse Storing PVC Bottles

1. Complete schedule of fuel:

- Description : PVC Bottles occupying 16 racks @ 8 m long x 1.6 m wide x 5 m high.
- Mass : 1 Rack =  $(8 \times 5 \times 1.6) \times 100 \text{ kg/m}^3$  (est.)  
= 6400 kg per rack.
- Surface Area : 1 Rack =  $(8 \times 5 \times 2) + (1.6 \times 5 \times 2) + (1.6 \times 8)$   
= 108.8 m<sup>2</sup> per rack.
- Calorific Value : CV = 17.8 MJ/kg
- Total Energy : 1 Rack =  $17.8 \times 6400 = 114,000 \text{ MJ}$   
Total Load =  $114,000 \times 16 = 1,824,000 \text{ MJ}$
- Burn Rate :  $m_F = 0.016 \text{ kg/s.m}^2$
- Peak HRR :  $Q_F = 2.84 \text{ MW/m}^2$  [NFPA 92B]
- Peak HRR per rack :  $Q_F = 2.84 \times (8 \times 1.6) = 36.4 \text{ MW}$
- Growth Rate :  $t_s = 75 \text{ s}$  (very fast)
- Time to max HRR [5.12] :  $t_g = (36.4)^{0.5} \cdot 75 = 452 \text{ s}$
- Vertical Vents = 2 off openings measuring 4 x 4 m  
= 32 m<sup>2</sup>
- Floor Area = 1200 m<sup>2</sup>
- Firecell Height = 8 m

2. **Design Strategy** - to design a smoke management system to cope with a growing fire limited to 1 rack only. Once the fire spreads beyond 1 rack the smoke management system is considered ineffective. As stated in Section 5.4, fire spread is not expected before total involvement of the rack. Once the rack is fully involved there is the possibility of fuel collapse onto neighbouring racks.

3. Limiting Smoke Layer Height to prevent flashover or failure of unprotected steelwork:

$$[8.3] \quad Q_{\max} = 36.4 \times 10^3 \text{ kW} = 1.3 \times 10^3 \cdot y^{5/2}$$

$$\Rightarrow y_c = 3.8 \text{ m (critical smoke clearance height)}$$

4. No Venting : the time that it would take for the smoke layer to drop below the critical smoke clearance height with no venting is:

$$[8.2] \quad y/h = 0.91 [t / (t_s^{2/5} h^{4/5} (A/h^2)^{3/5})]^{-1.45} \quad y = 3.8 \text{ m}$$

$$\Rightarrow 0.475 = 0.91 [t / 172.3]^{-1.45} \quad h = 8 \text{ m}$$

$$\Rightarrow t = 269.8 \text{ s (4.5 minutes)} \quad t_s = 75 \text{ s}$$

$$A = 1200 \text{ m}^2$$

5. Mass Flow (based on heat output and limiting smoke height to the height of the goods) :

$$[8.8] \quad Q_{\text{crit}} = 2.3 \times 10^5 y^{5/2}$$

$$\therefore Q_{\text{crit}} = 12.8 \text{ MW}$$

actual fire size = 36.4 MW;

assume convective heat output = 100%  $Q_f \Rightarrow Q_c = 36.4 \text{ MW}$   
 $\Rightarrow$  large fire

$$[8.10] \quad M = 5.3 \times 10^{-4} y Q_c^{3/5}$$

$$= 5.3 \times 10^{-4} \times 5.0 \times (36.4 \times 10^6)^{0.6}$$

$$= 91.2 \text{ kg/s}$$

6. Natural Vent Area, to keep the smoke layer above the height of the goods for 36.4 MW fire:

$$[8.14] \quad A_v = 1.94 \times 10^{-4} Q_c^{3/5} y / d^{1/2}$$

$$= 1.94 \times 10^{-4} \times (36.4 \times 10^6)^{0.6} \times 5.0 / 3.0^{1/2}$$

$$= 19.3 \text{ m}^2$$

7. Maximum Vent Size (Natural) :

$$[8.18] \quad (A_v)_{\text{crit}} = 2.94 (h-y)^2$$

$$= 2.94 \times 3.0^2$$

$$= 26.5 \text{ m}^2$$

The required vent size = 19.3 m<sup>2</sup> which is less than maximum vent size.

8. Area of Inlets : equating area of inlet openings to effective area of outlets.

$$[8.26] \quad 1/A_v^{*2} = (1/A_v^2) + (1/A_I^2) (T_o / (T_o + \theta))$$

let  $A_I = 2$  main doors @ 16 m<sup>2</sup> each

$A_v = 21 \text{ m}^2$  ( 6 natural roof mounted smoke vents)

$\theta = 60.7 \text{ }^\circ\text{C}$  (ASETBX upper layer gas temperature for a very fast fire after 452s)

$$T_o = 293 \text{ K}$$

$$\Rightarrow 1/A_v^{*2} = (1/21^2) + (1/32^2) (293 / 333.7)$$

$$\Rightarrow 1/A_v^{*2} = 3.13 \times 10^{-3}$$

$$\Rightarrow A_v^* = 17.9 \text{ m}^2$$

By providing an additional 14 m<sup>2</sup> inlet area, the effective outlet area = 19.3 m<sup>2</sup>, and therefore maintains the design 3.0 m smoke layer depth. This additional inlet area can be included as fresh air vents above the main doors.

#### 9. Control of Venting System

- 1) Vents on motorised dampers; activated by infra-red and/or ultra-violet flame detectors linked to alarm panel.
- 2) Two main doors would open automatically on receipt of a fire signal via the alarm panel.
- 3) The natural vents above the doors would be held open.

#### 10. Pressure Effects :

$$[8.25] \quad P_R = (P_B - P_W - P_I) \quad \begin{array}{l} P_B = \text{buoyancy pressure} \\ P_W = \text{wind pressure} \\ P_I = \text{inlet (expansion) pressure} \end{array}$$

$$[8.24] \quad \begin{aligned} P_B &= g \rho_o \Delta T_{s-a} d / (T_a + \theta) \\ &= (9.81 \times 1.2 \times 47.3 \times 3.0) / (333.7) \\ &= 5.0 \text{ Pa} \end{aligned}$$

$$[8.23] \quad \begin{aligned} P_W &= C_P \rho_o (V_w)^2 / 2 & V_w &= 10 \text{ m/s (assume)} \\ &= (-0.8 \times 1.2 \times 10^2) / 2 & C_P &= -0.8 \text{ (flat roof)} \\ &= -48 \text{ Pa} \end{aligned}$$

$$P_I = \text{(assumed) negligible due to low rate of rise of compartment temperature.}$$

$$\therefore P_R = 5.0 - (-48) - 0 \text{ Pa} \\ = 53 \text{ Pa}$$

$\therefore$  resultant pressure is positive and the smoke will discharge from the warehouse. This result is largely due to the suction pressure provided by the flat roof. If vents were on the windward side of the building this would result in a negative exhaust pressure and cause the natural ventilation system to be ineffective.

A possible roof vent layout would therefore be:

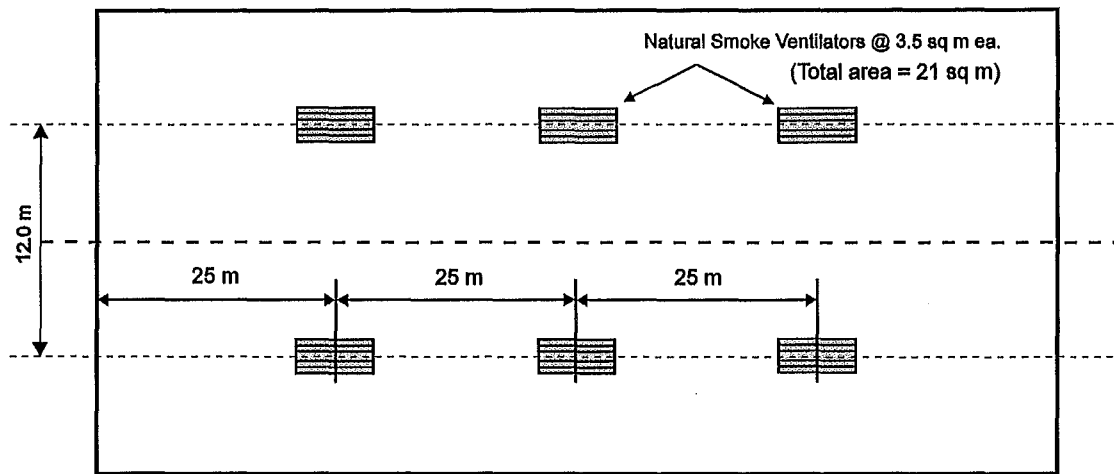


Fig. 8.5 : Proposed Smoke Ventilator Layout

## 11. Mechanical Extraction

### 1. Number of Extraction Outlets

$M_{crit}$  = critical flow rate through one outlet to prevent 'plugholing'

$$\begin{aligned}
 [8.20] \quad M_{crit} &= \beta (g d^5 T_a \Delta T_{s-a} / T_s^2)^{1/2} \quad (\beta = 1.8) \\
 &= 1.8 (9.81 \times 3.0^5 \times 293 \times 47.3 / 333.7^2)^{1/2} \\
 &= 31.0 \text{ kg/s}
 \end{aligned}$$

$$\begin{aligned}
 [8.21] \quad N &\geq M / M_{crit} \quad N = \text{Number of extract outlets} \\
 N &\geq 91.3 / 31.0 \\
 \Rightarrow N &\geq 3 \text{ outlets}
 \end{aligned}$$

2. Volume Extract Rate: based on a smoke layer constantly maintained at 3.0 m, a mass flow of 91.3 kg/s, and a smoke layer temperature of 333.7 K, the volume flow rate for the smoke is:

$$\begin{aligned}
 [8.11] \quad \rho_T &= (1.22 \times 290) / 333.7 \\
 &= 1.06 \text{ kg/m}^3 \\
 \Rightarrow V_F &= 91.3 \text{ kg/s} / 1.06 \text{ m}^3/\text{s} \\
 &= 86.1 \text{ m}^3/\text{s}
 \end{aligned}$$

A spreadsheet analysis can also be used to equate the effect of a fan operating at a constant extraction rate during the growth stages of a fire.

### EXAMPLE WAREHOUSE FIRE : MECHANICAL EXTRACTION

Time (s)	Heat Output (MW)	Smoke Clearance Height (m) [unvented] [Eqn 4.2]	Critical Heat Output (MW) [Eqn 4.8]	Mass Flow Rate (kg/s) [Eqns 4.9 & 4.10]	Temperature of Smoke Layer above Ambient [Eqn 4.5]	Cumulative Mass Smoke Flow (tonne)	Cumulative Mass Fan @65 cumees (tonne)	New Smoke Clearance Height (m)	Corrected Smoke Clearance Height (m)
0	0.00	8.00	41.63	0.0	0.0	0.0	0.0	8.00	8.00
30	0.16	8.00	41.63	12.6	1.6	0.4	0.0	7.74	7.74
60	0.64	7.74	38.33	19.7	3.8	1.0	0.0	7.33	7.33
90	1.44	7.33	33.44	24.8	6.3	1.7	2.3	8.00	8.00
120	2.56	8.00	41.63	35.8	8.3	2.8	4.6	8.00	8.00
150	4.00	8.00	41.63	43.4	10.7	4.1	6.9	8.00	8.00
180	5.76	8.00	41.63	51.4	13.1	5.6	9.2	8.00	8.00
210	7.84	8.00	41.63	59.6	15.5	7.4	11.5	8.00	8.00
240	10.24	8.00	41.63	68.2	17.9	9.5	13.7	8.00	8.00
270	12.96	8.00	41.63	77.3	20.2	11.8	15.9	8.00	8.00
300	16.00	8.00	41.63	86.8	22.6	14.4	18.2	8.00	8.00
330	19.36	8.00	41.63	96.7	24.9	17.3	20.3	8.00	8.00
360	23.04	8.00	41.63	107.2	27.2	20.5	22.5	8.00	8.00
390	27.04	8.00	41.63	118.1	29.5	24.1	24.7	8.00	8.00
420	31.36	8.00	41.63	129.5	31.7	27.9	26.8	7.16	7.16
450	36.00	7.16	31.55	129.7	35.0	31.8	29.0	5.80	5.80
480	36.40	5.80	18.64	105.8	38.0	35.0	31.1	4.96	4.96
510	36.40	4.96	12.58	90.4	40.2	37.7	33.2	4.45	4.45
540	36.40	4.45	9.63	81.2	41.8	40.2	35.2	4.16	4.16
570	36.40	4.16	8.12	75.9	42.8	42.4	37.3	3.99	3.99
600	36.40	3.99	7.32	72.8	43.5	44.6	39.4	3.90	3.90

This spreadsheet involves correcting the smoke layer heights to account for the smoke extracted. The resulting fan capacity of 65 m<sup>3</sup>/s is determined by looking at the cumulative extract smoke at 450 seconds and ensuring that there is at least a smoke clearance height of 3.0 m. After 450 seconds it is assumed that the single rack reaches its maximum heat output and the fire spreads to neighbouring racks and is uncontrollable. This allows only 7.5 minutes for complete evacuation and any internal fire fighting.

In conclusion, it is considered that for this example the location of natural roof ventilators is more economic than mechanical ventilation. The effect of roof skylights was not considered due to the low upper layer temperatures at this stage of the fire growth.

## 8.6 Smoke Curtains

Smoke curtains are sometimes employed to limit horizontal travel of smoke, and to limit excessive cooling of the smoke layer. Cooling can lead to reduced efficiency of the venting system and mixing of the smoke between the upper and lower layers.

If designed in conjunction with a smoke ventilation system, the fires can theoretically be controlled to one zone of the compartment. Smoke curtains can be permanently in place or can be dropped upon signal from the fire detection system. Also, smoke curtains of different depths can be installed to direct the smoke overflow away from critical areas [Patterson, 1986].

The recommended maximum distance between screens is eight times the ceiling height, and a minimum distance of twice the ceiling height (ceiling height is measured to the center of the vent). The maximum recommended area is 2000 m<sup>2</sup>



for storage buildings [Hinkley, 1992]. The minimum depth for flat ceiling compartments is recommended at  $(h/5)$ , with the curtains terminating 500 mm below the design smoke layer base [Smoke Ventilation Association, 1990]. Smoke curtains should be constructed from substantial, non-combustible materials that will resist the passage of smoke.

## 8.7 Interaction of Roof Ventilation and Sprinkler Systems

The interaction between smoke ventilation and sprinkler systems has been a matter of some contention. There has been a concern that smoke venting delays sprinkler operation, and therefore allows a fire to spread unnecessarily. The opposing viewpoint is that sprinkler operation reduces smoke temperatures and buoyancy, and can undermine the effectiveness of the venting system [Hansell, 1993].

Smoke venting has distinct advantages in lowering compartment temperatures, and reducing the effects of smoke obscurity and damage. If expected to operate in conjunction with a sprinkler system, consideration needs to be given to the likely reduction in buoyancy, and a recommended increase in extraction volumes. Also, there needs to be adequate protection of any fusible links on roof vents from possible sprinkler spraying.

### 8.7.1 Cooling Effect of Sprinklers and Vents

Heselden [1984] provided a relationship that assesses the cooling effect of the smoke layer due to convection, radiation, sprinklers and venting:

$$\Delta T_{v-a} = \Delta T_{s-a} \frac{(2M C_P - M_e A C_P - A U - 880 y M_w)}{(2M C_P - M_e A C_P + A U)} \quad (\text{K}) \quad [8.27]$$

$\Delta T_{v-a}$  = temperature above ambient of vented smoke

$\Delta T_{s-a}$  = temperature above ambient of smoke entering upper layer

$M$  = mass flow rate of smoke into layer (kg/s)

$C_P$  = specific heat of air at  $\theta + T_o$  [J/kg K]

$M_e$  = mass extraction rate of venting, per unit area of ceiling (kg/m<sup>2</sup>s)

$A$  = horizontal area of ceiling being considered (m<sup>2</sup>)

$U$  = heat transfer coefficient of roofing material (W/m<sup>2</sup>K)

$y$  = smoke layer depth (m)

$M_w$  = total downfall of water over the ceiling area being considered (kg/s)

This can be used to determine the effect sprinkler and venting action has on a design fire, especially in terms of fire spread and possible flashover. The equation is based on standard spacings for sprinklers at roof level, assuming a square area of operation (instead of radial) and uniform heat transfer.

### 8.7.2 Control of Roof Vents in Sprinklered Environments

It is generally recommended that sprinklers should operate before roof vents [Heselden, 1984]. This ensures maximum benefit is made of the sprinkler operation, rather than delay operation through lowered temperatures.

This can be easily achieved through careful selection of operating temperatures and use of automatic controls. If fusible links are the means of operation of natural vents, then the release temperature should be slightly above the sprinkler head temperature rating. The preferred control mechanism is for a sprinkler flow switch to provide a signal that causes extract fans or vent shutter motors (throughout the zone) to switch to the 'operating' position. A 'fail-safe' condition should also be provided that ensures the vents open on a mechanical or electrical malfunction.

Given that the main benefit of a smoke ventilation system in this circumstance is to aid fire fighting operations (due to the sprinklers controlling the effects of the fire), it is important to provide manual over-ride control of motorised equipment at the Fire Service panel.

Tests undertaken by the Factory Mutual Research Corporation in 1974 [Heselden, 1984], showed that operating vents in conjunction with sprinklers increased water demand and fuel consumption, but improved visibility conditions. This has been substantiated by Fire Service incident records reviewed by Heselden [1984]. No cases were reported where venting appeared to have an adverse effect on the fire.

A typical case example was a fire in a sprinklered foam-rubber factory in Port Elizabeth, South Africa, on 22 September 1973. The roof vents greatly assisted the firemen in locating and controlling the fire.

### 8.7.3 Are Roof Vents Necessary in Sprinklered Environments?

The final question is how essential are smoke vents if the sprinkler system is expected to control and ultimately extinguish the fire? High rack storage facilities that are protected by in-rack sprinklers, are considered to have adequate protection without roof vents.

Without roof vents however, there is expected to be significant smoke damage. The resultant smoke will lose buoyancy due to the sprinkler action, and is normally expected to envelop the compartment area. Roof vents provide a means of releasing generated smoke that has risen to the underside of the roof. Translucent skylight panels can not be relied upon to act as natural smoke ventilators. The action of the sprinklers ensure that the upper layer smoke temperatures never reach the expected melting temperature of around 300 - 350 °C.

It is recommended that roof venting is included in a sprinklered industrial building because of the following benefits:

- minimise smoke damage.

- aid fire service operations.
- limit the number of sprinklers operating.
- allow purging of smoke once the fire is under control.

#### **8.7.4 Are Sprinklers Necessary in a Vented Environment?**

Sprinklers are recognised as being the only effective way in controlling a warehouse fire [Davis & Moore, 1991; Hansell, 1993]. Sprinklers combine the advantages of both a detection and suppression system. Detection systems, such as flame detectors or a VESDA system, could be installed to provide an early fire warning, but the detected fire can only be controlled if there is rapid and effective human intervention and this is not usually possible. The potential conflict of roof vents operating and delaying the activation of sprinklers can be avoided with careful design, as discussed in Section 8.7.2..

### **8.8 Conclusions**

1. Roof vents provide smoke control within a compartment, and therefore assist with escape systems, fire fighter operations, and limitation of damage during the initial stages of a fire.
2. Roof vents can be provided by natural vents or mechanical extraction. Both techniques rely on the buoyancy pressure of the fire to drive the smoke outside.
3. A roof venting system should form part of a fire design strategy. It is not a substitute for sprinklers or other extinguishing systems.
4. Sprinklers operating without roof vents are expected to control the fire, but cause greater smoke and water damage.
5. Sprinklers and roof vents should be integrated where possible. Sprinklers are recommended to operate first, with roof vents minimising smoke damage and assisting Fire Service operations.

## 9.0 STRUCTURAL PERFORMANCE

The primary objectives in fire safety design is to ensure that occupants can evacuate safely from a burning building and to control the spread of fire. The NZ Building Code explains the need for controlling fire spread in clause C3.2 [BIA, 1992]:

*Buildings shall be provided with safeguards against fire spread so that:*

- a) Occupants have time to escape to a safe place without being overcome by the effects of the fire,*
- b) Firefighters may undertake rescue operations and protect property,*
- c) Adjacent household units and other property are protected from damage, and*
- d) Significant quantities of hazardous substances are not released to the environment during fire.*

The Fire Service are considered to play an important role in meeting this criteria, as discussed in Sections 10 and 11. The likelihood of fire spread is also strongly influenced by active fire protection systems and fire rated building systems. For limiting fire spread to adjacent properties, boundary walls become the most important structural feature, where these in turn are dependant on the primary support structures.

### **Industrial Buildings**

Most single storey industrial buildings consist of a concrete floor slab with roof and walls supported by steel portal frames. The roof is usually thin corrugated steel sheeting supported on purlins with 5% to 15% of the roof area in translucent plastic skylights. Most older buildings have timber purlins whereas new buildings are expected to have cold-rolled steel purlins. Exterior boundary walls are often precast tilt-up reinforced concrete panels, otherwise reinforced concrete masonry. Walls remote from boundaries are usually thin corrugated steel sheeting supported on timber or steel girts.

Walls near boundaries are required to have fire resistance, including lateral stability in the after-fire condition when the roof has collapsed. For this reason, it is common to encase all or part of the steel portal frame column leg with concrete, or to use a reinforced concrete column for the lower part of the portal frame leg. There are usually very few interior walls, where these are expected to be light

partitions with sheet lining on light timber framing, unless fire resisting interior walls are provided for compartmentation.

### **Objective**

The objective of this section is to recommend a suitable technique for designing external boundary walls, with due regard to the 'S' rating system, suitable primary support design, and the preferred failure mechanism. This section also endeavours to establish a limit on the maximum fire rating necessary for a boundary wall.

## **9.1 Prescriptive Solutions**

### **9.1.1 Code Summary**

Comparative prescriptive requirements within other countries' building codes is made by O'Meagher et al [1991], as shown in Table 9.1:

Overseas Codes	Fire Rating Requirements		
	Steel Column (if present)	External Walls	Steel Roof
BCA	No FRL requirements	90 minutes FRL required	No FRL requirements
BOCA	3 hr fire-rating required	3 hr fire-rating required	No fire-rating requirement
UBC	1 hr fire-rating required	1 hr fire-rating required	No fire-rating requirement
NBCC	2 hr fire-rating required	2 hr fire-rating required	No fire-rating requirement
SBC	No fire-rating requirement	2-3 hr fire rating required	No fire-rating requirement
BBR	½-2 hr fire rating required depending on area	½-2 hr fire rating required depending on area	No fire-rating requirement
SBR	No fire-rating requirement	Nominal fire rating required	No fire-rating requirement

Table 9.1 : Code Requirements - Single-storey Buildings Located Close to Site Boundary  
[O'Meagher et al, 1991]

Abbreviations used in the table:

- BCA - Building Code of Australia, Australia Uniform Building Regulations Co-ordinating Council, 1990
- BOCA - Building Officials Conference of America, National Building Code, Building Officials and Code Administrators International, Inc., Country Club Hills, Illinois, USA.
- UBC - Uniform Building Code, International Conference of Building Officials, Whittier, California, USA, 1988.

NBCC - National Building Code of Canada, Associate Committee on the National Research Council of Canada, Ottawa, Canada, 1985.

SBC - Swedish Building Code, SBN 1980.

BBR - British Building Regulations, 1985, Approved Document B.

SBR - Swiss Building Regulations.

The maximum fire rating required for external walls and steel supporting columns from this Table for any Code is 3 hours only.

### 9.1.2 British Regulations

Expanding on one code: the British Building Regulations, Approved Document B, shows that for single storey industrial buildings the minimum required fire resistance rating is dependant on building height and type of use. This document also includes minimum separation distances beyond which fire ratings do not have to be applied.

Purpose Group		Minimum Period of Fire Resistance (Min)			
Use	Sprinklered?	BH not > 5m	BH not > 20m	BH not > 30m	BH > 30m
Industrial “	no	60	90	120	not permitted
	yes	60	60	90	120
Storage “	no	60	90	120	not permitted
	yes	60	60	90	120

Note: BH = Building Height

Table 9.2 : Minimum Periods of Fire Resistance [British Building Regulations, Approved Document B]

For example, an 8 m high single storey industrial building without sprinkler protection requires a minimum 90 minute boundary fire resistance rating. This is regardless of fire load or ventilation characteristics.

### 9.1.3 NZ Building Code

The NZ Building Code Acceptable Solutions include a table for determining the fire rating for a building's external walls based on fire loading and ventilation characteristics. The table presents an equivalent fire severity ( $t_e$ ) that is then modified by a factor of 0.5 or 1.0 depending on whether there is sprinkler protection or no sprinkler protection (respectively). The following table is an abbreviated form, and includes an example to highlight the determination process.

$A_v/A_f$	FLED = 400 MJ/m <sup>2</sup>			FLED = 800 MJ/m <sup>2</sup>			FLED = 1200 MJ/m <sup>2</sup>		
	$A_h/A_f$			$A_h/A_f$			$A_h/A_f$		
	0.00	0.10	0.20	0.00	0.10	0.20	0.00	0.10	0.20
0.05 or less	65	36	30	130	72	60	195	108	90
0.10	45	27	24	89	55	49	134	82	73
0.15	32	23	22	64	47	44	91	70	66
0.20	25	21	21	50	43	42	76	64	63
0.25 or greater	22	21	21	44	41	41	66	62	62

Table 9.3 : Values of  $t_e$  for Calculating 'S' Values [BIA, 1991] - ( $A_v$  = Area of vertical openings;  $A_f$  = Area of floor;  $A_h$  = Area of horizontal openings; FLED = Fire Load Energy Density).

Example: An industrial building protected by sprinklers, has an assessed FLED of 1200 MJ/m<sup>2</sup> within a single fire compartment, plus the following area characteristics:

Floor Area ( $A_f$ ) = 1000 m<sup>2</sup>

Area of Vertical Openings in external walls ( $A_v$ ) = 50 m<sup>2</sup>

Area of Horizontal Openings in Roof ( $A_h$ ) = 80 m<sup>2</sup>

$$\therefore A_h/A_f = 0.05$$

$$A_v/A_f = 0.08$$

Interpolating from Table 9.3 results in  $t_e = 120$  minutes.

$$\text{'S' Rating} = t_e \times k \quad k = 0.5 \text{ for sprinklered firecells}$$

$$\therefore \text{'S' Rating} = 120 \times 0.5 = 60 \text{ minutes.}$$

This means that any external walls causing an exposure risk to neighbouring property must have a fire rating of at least 60 minutes.

### ***Eurocode Formula***

Table 9.3 (extracted from BIA [1991] ) has been produced using the "Eurocode formula" for time equivalence given by equation 5.9:

$$t_e = e_f k_b w_f \quad [5.9]$$

It is important that users of Table 9.3 or equation 5.9 be aware of the derivation, significance and limitations:

1. The equivalent fire severity  $t_e$  is the equivalent time of exposure to the standard fire that would produce the same maximum temperature in a protected structural steel member given a complete burnout of the firecell. The method was developed for protected steel members, but it is considered reasonable for materials other than steel [Buchanan, 1994]. The value of  $t_e$  is therefore an equivalent time for comparing real fires with the standard fire. It is not an estimate of fire duration.
2. Equation 5.9 is based on a quoted and widely used formula developed twenty years ago by Margaret Law [CIB, 1986]. However, the ventilation factor ' $w_f$ ' is not the same as the original, as it has been modified to allow for ceiling height and horizontal openings. Their derivation has never been published, and it is believed to be an empirical estimation from a number of tests.
3. The time equivalent formula was developed from tests on small rooms. Recent tests on a compartment 6 m wide by 20 m long by 3 m high show that it is not conservative for large compartments [Kirby et al]. No validation is known of in compartments with a ceiling height greater than 3 m.
4. The time equivalent formula applies to compartments where the roof and walls remain intact (other than ventilation openings) for a complete burnout. The formula cannot be used for buildings when the roof collapses during the fire.

From this information it can be seen that the time equivalent formula (equation 5.9 or Table 9.3) is totally inappropriate for single storey industrial buildings. However, in view of the lack of better design tools, the equivalent time formula is probably a conservative estimate of required fire resistance.

### ***Benefits of Sprinklering***

The concession for sprinklers of halving the required fire resistance rating is considered conservative. Sprinklers are expected to at least control the fire to the growth area at the time of activation. This is achieved by a mixture of cooling, oxygen depletion, and prewetting of adjacent fuels. In a sprinkler controlled fire the compartment temperature is not expected to exceed 300 °C, given that most sprinkler heads are rated at temperatures ranging from 63 °C to 93 °C, and allowing for an activation time delay.

Also within New Zealand, sprinkler systems are surveyed biannually to ensure that are operationally sound, and that the protected risk remains within the design limits. For these reasons it is considered that a fire resistance rating of 60 minutes for boundary walls would be sufficient.



### 9.1.4 Maximum Fire Resistance Rating

Traditionally prescriptive codes have not required a maximum fire rating for a compartment separation in excess of 4 hours. The NZ building code used before the NZ Building Act 1991, was NZS 1900 Chapter 5 [SANZ, 1984]. This document required 4 hour fire resistance rating for high risk occupancies where the structure was less than 4.5 m from the boundary. As seen from Table 9.1, major overseas codes do not require greater than 3 hour fire rating, regardless of fire loading or severity.

It is considered that an allowance should be made for Fire Service intervention in establishing fire resistance ratings. As discussed further in Section 11 the primary objective for the Fire Service once all occupants have been accounted for, is to ensure that there is no fire spread to neighbouring property. The quantity of water required to achieve this is considerably less than the quantity necessary for full suppression, and an assessment can be made of the effect of the Fire Service once factors such as available water supplies and notification times are known.

### 9.1.5 Specific Fire Engineering Design

The NZBC Acceptable Solutions state that for firecells containing combustible material with a FLED exceeding  $1500 \text{ MJ/m}^2$  or burning rates indicating a very fast growth rate [refer NFPA, 1991], then specific fire engineering design (SFED) is required to determine the appropriate fire rating.

The basis of specific fire engineering design is scenario analysis, where a large number of possible fire scenarios must be investigated (Buchanan, 1994). Such design must be carried out (and subsequently reviewed) by suitably qualified professional fire engineers. Numerical calculations are available for individual components of the process, but the final assessment of safety is by opinion, not calculation, because the performance requirements of the code are not quantified. This results in a number of different design strategies and solutions, without a quantifiable level of safety.

## 9.2 Fire Behaviour

The fire development process is discussed in Section 5.0. This process is simplistic in the following assumptions:

- i. The fire grows constantly until restricted by available ventilation.
- ii. Fire spread results in all exposed fuel surfaces burning simultaneously.

- iii. The rate of burning does not diminish during the course of the fire.

This type of outcome is acceptable for small compartments, but for large compartments such as within warehouses, fires often do not develop and spread unless there is a suitable mechanism for fire spread, and substantial ventilation is available [Thomas and Bennetts, 1992]. Flashover is not expected to occur until a substantial local fire has developed possibly resulting in parts of the structural frame being exposed to considerable heat. Also the presence of large fuel loads can result in charred fuel shielding the fuel below, and slowing down the burning rate.

If the roof collapses, the fire is no longer ventilation controlled, and the burning rate depends on the surface area of fuel available for combustion. Construction materials have some influence on the level of roof collapse, as steel purlins may allow the steel roof sheeting to remain more intact, as opposed to timber purlins which burn away. Also the failure may be localised depending on the layout of fuel and compartment temperature profiles.

To estimate the time of roof collapse it is necessary to use a fire growth model in conjunction with a heat transfer model such as TASEF [Sternier and Wickstrom, 1990]. The time at which critical temperatures in the steel members are exceeded can be determined and thereby implying roof collapse. This process assumes that fire fighting will not have any effect on fire development so allowance can be made for Fire Service intervention if appropriate.

After roof collapse, estimation of temperatures adjacent to boundary walls becomes difficult to determine. Drysdale [1985] indicates that flame temperatures can be expected to range from 950 °C to 1200 °C, depending on the fuel being burnt. The lower figure is considered more relevant due to combustion inefficiencies.

All of these factors contribute to making determination of the appropriate fire resistance rating very difficult. The techniques currently used are considered conservative, mainly because they ignore the effect of Fire Service intervention, and do not account for the diminished effect of the fire on structural systems after roof collapse (ie. minimal convective heat transfer).

It is considered that a maximum fire rating should be established, and a 4 hour fire rating is considered a suitable value based on buildings containing goods exceeding a fire load energy density of 1500 MJ/m<sup>2</sup> and not containing active fire protection. This is with reference to the maximum values used in other Codes and the expected Fire Service response, as well as the anticipated reduction in fire severity once the building roof collapses and the fire is burning in the open air. This value should only be reduced if fire engineering design proves that either the design fire, separation distance or building design result in a lesser maximum exposure period or risk.

The alternative (and current) approach of estimating the required fire resistance by attempting to equate real fires to standard test fires, is discussed in the following sections. This is followed by structural design recommendations to lower the risk of fire spread if there is a failure condition.

### 9.3 *Fire Resistance*

#### 9.3.1 *Standard Fire Test*

Fire resistance is the ability of an element of building construction to perform its function as a barrier or structural component during the course of a fire. As discussed by Buchanan [1994], the fire resistance rating ( $t_r$ ) may be determined either by experimentation (ie. to ISO 834) or calculation. Calculation techniques are provided in the Fire Engineering Design Guide [Buchanan, 1994] for determining whether structural members (ie. steel, concrete, or timber) can withstand the design fire loading for the estimated fire severity period. These calculations also consider the effects of passive fire protection systems applied over the structural members (ie. such as concrete encasement over steel members).

Fire resistance rating for a construction system is usually determined by testing a full scale sample, possibly under load, to failure as it is exposed to a 'standard fire' as defined by the temperature-time variation of a fire in a furnace. The ISO 834 standard test fire as described below is a common example of a 'standard fire'; noting that temperatures are usually held around the 1000 °C level.

$$T = 345 \log_{10}(8t + 1) + T_o \quad (^\circ\text{C}) \quad [9.1]$$

$t$  = time (min.)

$T_o$  = initial temperature (°C)

#### 9.3.2 *Methods of Calculating Required Structural Fire Resistance*

##### *Integrity and Insulation*

The validity of this 'standard fire' test method with respect to current knowledge of real fires needs to be questioned. Ventilation and the nature, distribution and quantity of fuel all have a significant effect on duration and severity. The performance of a structural member or barrier in a 'non-standard' fire can be approximated by equivalent fire severities for predicted fire behaviour curves. Ingberg hypothesised that if the areas under the time-temperature curves for the standard fire and a real fire are equal, then the severities are equal [Drysdale, 1985]. Summarising the methods available for determining fire severity:

### 1. Equivalence to Standard Fire

If the actual fire can be considered equivalent to a certain duration of exposure to the standard fire (by means of a time equivalent formula - equation 5.9 for example), then that equivalent fire severity can be compared directly with a fire resistance rating from a standard fire test.

### 2. Duration of Burning

The total duration of burning can be calculated in the ventilation and fuel controlled stages of the fire. This can be compared with a fire resistance rating from a standard test.

### 3. Real Fire Calculation

The alternative is to use the time temperature curve for the expected real fire directly without reference to the standard fire.

If the time temperature curve is known, any element of structure can be exposed to that fire in a calculation to estimate whether it has sufficient fire resistance to carry the imposed loads and contain the fire.

Of the three methods, method 1 is most suitable for a fire in compartments with no roof collapse (i.e. the time equivalent formula is valid) and for materials which have extensive fire resistance test data (i.e. light timber frame walls).

Method 2 is more suitable for unenclosed fires but is very conservative as the intensity of the fire is not expected to match the standard test profile for time versus temperature.

Method 3 is appropriate for materials where internal temperatures can be calculated without too much difficulty (ie. protected steel or concrete members) and for enclosed fires. This method is more difficult to calculate but potentially more exact.

## **Stability**

Using NZS 4203:1992, the stability requirement can be met by providing resistance to a notional face load of 0.5 kPa in the after-fire condition, with no calculations of lateral loading during the fire. This notional load is intended to give the wall resistance to being pulled down by collapsing portal frames during the fire, and some resistance to wind loads during or after the fire. It is common to encase all or part of the steel portal frame column with concrete, or to use a reinforced concrete

column for the lower part of the portal frame leg, but it is not possible to do a calculation for structural behaviour of a cantilever wall during a fire without information on lateral loads, and no loads are given in NZS 4203, or elsewhere.

#### 9.4 *Structural Behaviour*

The key question posed by O'Meagher et al [1990] was does it matter if there is failure of primary structural elements within single storey industrial buildings during a fire? If the roof collapses due to failure of the rafters, then the fire becomes an open air fire and the exposure temperatures on the boundary walls reduce significantly. They are only subjected to radiation from the fire, when previously they were affected by both radiation and convection within the compartment.

If the supporting elements for the boundary walls then fail, will this cause an exposure problem for neighbouring properties? Again O'Meagher et al. argue that it does not as long as the boundary (concrete) walls are tied together and fall inwards. This action will still maintain an adequate separation distance by virtue of the resulting horizontal projection being equal to the wall height (usually at least 5 m). As discussed in Section 5.0 if the neighbouring property is in an industrial zone and has a combustible facing wall, it will be at least 3-4 m away from the title boundary, giving a total separation of at least 8-9 m.

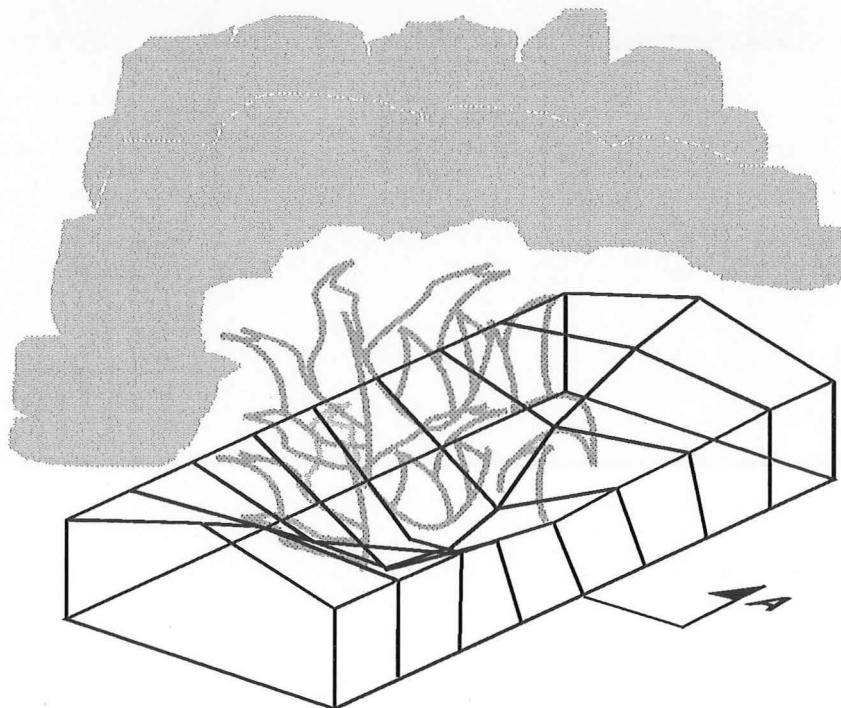


Figure 9.1 : Collapse of a Portal Frame Building with Tied Concrete Wall Panels

The Australian research concluded that for portal frames with typical restraint at the base of the column and assumed heating situations, the inwards collapse mode occurs irrespective of whether:

1. the steel column is fire protected or not,
2. the frame provides lateral support to a wall or not,
3. the steel frame is restrained against in-plane lateral movement by the cooler parts of the roof or not, and
4. the entire frame is heated.

This mechanism is shown in figure 9.1 and figure 9.2.

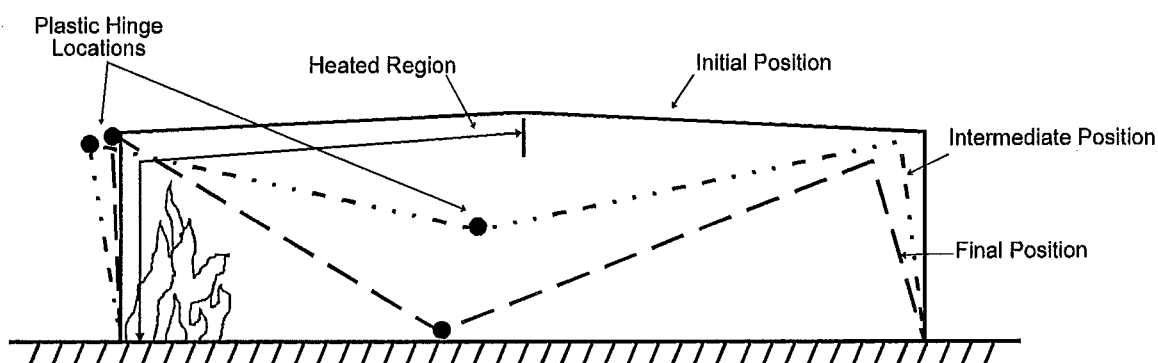


Figure 9.2 : Section A-A; Collapse Mode of a Steel Portal Frame [Bennetts, 1990]

Potter (1994) supports this concept, but emphasises the importance of designing the connections between panels and structure to ensure they do not fail in the early stages of a fire. As the wall panels are heated they tend to move outwards. The pulling of the panels inwards will only occur once the heat load is high enough and sustained for a sufficient period. This allows the frame to soften and result in the plastic hinge mechanism shown in figure 9.2.

#### 9.4.1 Building Code of Australia

The Building Code of Australia included in its Amendment No. 7 issue, a revised clause (C1.11) titled 'Performance of External Walls in Fire' [AUBRCC, 1995]. The scope for this clause reads:

*'This specification contains measures to minimise in the event of a fire the likelihood of external walls covered by Clause 2 collapsing outwards as*

*complete panels and the likelihood of panels separating from supporting members'*

It is recommended that this approach is adopted in the design of external boundary walls, both for controlling the spread of fire and for the safety of fire fighting operations. The listed general requirements are:

- a) *Cast-in inserts and fixings must be anchored into the panel with welded bars or be fixed to the panel reinforcement. This is to ensure there is some attachment for the fixing elements after the concrete shear cone has failed.*
- b) *Cast-in inserts for top connections and fixings acting together must be able to resist an ultimate load of two times the larger of the forces required to develop-*
  - *the ultimate bending moment capacity of the panel at its base; or*
  - *the overturning moment at the base of the panel arising from an outwards lateral displacement at the top of the panel equal to one tenth of the panel height.*

This requirement details the minimum strength capacity for top inserts/fixings so that the collapsing framework/roof structure will pull the panel inwards.

- c) *Top connections of the panel exposed to fire, such as clips and drilled-in inserts, acting together must be able to resist an ultimate load of six times the larger of the forces required to develop the moment specified in (b). It is believed that drilled-in inserts and clips will suffer a greater strength loss due to exposure to fire than will cast-in inserts.*
- d) *Lateral supporting members and their connections must be designed to resist the connection forces specified in (b) and (c) and in the case of an eaves tie member the force in the member must be determined assuming that it deforms in a manner compatible with the lateral displacement of the wall panels, and that it acts in tension only. Lateral supporting members are usually roof beams or trusses.*
- e) *External wall panels that span vertically must have at least two upper connections per panel to the supporting member, except that where a number of panels are designed to act as one unit, (eg. tongue and groove hollow-core panels), only two upper connections are required for each unit. The emphasis is on involving all of the panels acting together as one unit.*

- f) External wall panels that span horizontally between columns must have at least two connections at each column.*

The New Zealand solution of encasing the portal columns (to a mid-height) with concrete assists in this protection of panel connections, but it is considered that the protection should also apply to tie members and high level connections points.

## **9.5 Conclusions**

1. To reduce the probability of fire spread to neighbouring property from fire in unsprinklered buildings with  $FLED > 1500 \text{ MJ/m}^2$ , walls close to boundaries should be provided with a fire resistance rating of 4 hours.
2. This rating can be reduced if it is proven that either the design fire, separation distance or building design will result in a reduced exposure risk.
3. If the fire resistance rating provided is less than the severity of the expected fire, the assistance of the Fire Service will be required to prevent fire spread to neighbouring property.
4. The use of equivalent time formulae are considered conservative due to no allowance for reduced fire severity for open air fires and the effect of Fire Service response.
5. The critical elements in the boundary wall design are the connections between the panels and support structure, and between adjacent panels. These need to be designed to ensure that the walls function as one unit, and do not collapse outwards during a fire.



## 10.0 FIRE SERVICE INTERVENTION

Intervention by the Fire Service is an important consideration in the fire design of single storey industrial buildings. The New Zealand Fire Service have a clear legislative requirement to *make provision in every Fire District for the prevention of fire, the suppression and extinction of fires, and the safety of persons and property endangered by fire* [Fire Service Act 1975, s170(a)].

The following section aims to highlight Fire Service responsibilities and capabilities. Reference is made to their dependence on conditional events (ie. access to adequate water supplies) to complete a successful fire fighting procedure.

### 10.1 Legislative Requirements

The following Acts place a dependence on the Fire Service either directly or through being part of the design process. Their role is referenced with particular regard to the fire protection of industrial buildings and in preventing the spread of fire:

#### 10.1.1 Building Act 1991

The NZ Building Act, through its Regulations, states as its objective for meeting Spread of Fire requirements [Clause C3.1]to:

- a) *Safeguard people from injury or illness when evacuating a building during fire.*
- b) *Provide protection to Fire Service personnel during fire fighting operations.*
- c) *Protect adjacent household units and other property from the effects of fire.*
- d) *Safeguard the environment from adverse effects of fire.*

The Acceptable Solutions provide passive and active fire protection details to achieve these objectives for buildings that do not exceed a Fire Load Energy Density of 1500 MJ/m<sup>2</sup>. Buildings that exceed this value are often industrial buildings. They require specific fire engineering design methods to meet the fire safety objectives. The involvement of the Fire Service can form part of an alternate design method, as outlined in Section 11.

### 10.1.2 Fire Service Act 1975

The Fire Service have a clear legislative requirement to *endeavour by all practicable means to extinguish and prevent the spread of the fire* [Fire Service Act 1975, s28(2)], including the requirement to *make provision in every Fire District for the prevention of fire, the suppression and extinction of fires, and the safety of persons and property endangered by fire* [Fire Service Act 1975, s17o(a)]. Specific procedures stated in the Act, include:

1. Issuance of operational instructions to achieve these goals (s17N (a) ).
2. Publication of a Code of Practice for Fire Fighting Water Supplies (s17N (b) ).
3. Provision for cooperation between the Fire Service and territorial authorities and regional councils (s17o (d) ).
4. Promotion of fire safety throughout New Zealand (s20 )
5. Access onto property for the purposes of pre-incident planning and active fire fighting (s28 & s29).

Section 30(3) of the Act requires the Fire Service to publish a Code of Practice for Fire Fighting Water Supplies, and Section 30(2) requires the Fire Service to inspect and test hydrants and auxiliary supplies to determine sufficiency for fire fighting operations in accordance with the Code of Practice. This has to be reported to the Territorial Authority.

The resulting Water Supply Classification Table is as follows [NZFS, 1992].

Risk Classification	NZFS Response	Minimum Water Flow Required (l/s) (Reticulated)	Max. No. of Hydrants from which the Flow Shall be Obtained Within a 270m Radius
A	High	200	8
B	High	200	8
C	High - Normal	100	4
D	Normal	50	3
E	Normal - Low	25	2

Table 10.1 : Water Supply Classification Table

The classes of fire risk for determining water supply are:

1. Class A - The central urban areas of Auckland and Wellington presenting a serious risk of fire.
2. Class B - Congested industrial and commercial areas in larger cities.

3. Class C - Concentrated built up areas of cities not included in A or B.
4. Class D - Business and commercial areas not included in A, B, C or D.
5. Class E - Any area with a reticulated water supply not included in A, B, C, or D (most housing).

It is implied that if these water supplies are made available by Territorial Authorities, the Fire Service should be able to effect its fire fighting obligations.

Section 43 of the Fire Service Act provides the criteria for limitation of liability. Acceptable defence for alleged non-performance includes compliance with the standards approved by the Commission under the Act. This means that if the Fire Service undertake their duties in accordance with operational instructions, then they fulfil their obligations.

### **10.1.3 Local Government Act 1974**

The question of guaranteed water supply is covered under the Local Government Act 1974 (Section 648) [Buchanan, 1994]. The Territorial Authority is required to keep all pipes in which fire hydrants are fixed charged with water at all times, excepting unusual circumstances (as listed in the Act).

## **10.2 Fire Service Performance**

### **10.2.1 Role of the Fire Service**

The Fire Service have a clear obligation to make provision in every Fire District for:

- prevention of fire
- suppression and extinction of fires
- safety of persons and property endangered by fire

There is also today an increasing demand for the Fire Service to provide a variety of ancillary emergency services, such as:

- controlling and cleaning chemical spills
- cutting and cleaning at vehicular accidents
- flood relief
- height rescues

An associated concern with this developing role is the demand on resources, and the unavailability of sufficient equipment in a major fire. It is assumed that attendance to fires remains the highest priority, and contingencies are in place to overcome resource limitations. This includes calling in appliances from other sectors, and calling in off-duty personnel.

Bedford [1993] states that *“it is the objective of the NZ Fire Service to respond to every incident where life or property is endangered by fire with a predetermined number of pumping appliances, and to arrive within the time set for the various classes of risk which may be present in any fire district”*. This objective is for properties within urban areas, including small rural towns. Obviously a different approach is required for rural areas where an industrial site is located, such as Canterbury Timber Products at Sefton, Canterbury, or Comalco Aluminium Smelter at Tiwai Point, Southland.

### **Attending Fires**

On attending an incident, the Officer-in-Charge is required to assess the state of the fire and call for support as required. The first priority at the fireground is usually to ensure all occupants have been evacuated from the building. This could require firefighters searching the interior of the building for unaccounted persons, and involve entry into hazardous areas.

Fire fighting is usually initiated once all occupants have been cleared, or in support of any rescue operations. Defensive or attacking procedures will be initiated depending on:

- water supplies
- hoses, men and pumps available
- size of fire
- access into the building
- exposure danger
- spread of fire risk

The first aim is to contain the fire so that it will not spread. The fire may be able to be confined to a firecell, or to the building. It is extremely unusual if it is allowed to spread to neighbouring buildings. When the fire is contained, then the opportunity to attack could occur. The safety of the crews is a critical factor in this decision.

Crews are usually stood down and the fireground closed once the fire is completely extinguished, contents turned over and a standby period completed.

### 10.2.2 Fire Service Performance

The performance of the Fire Service at a fire incident can be measured in terms of events. Listing the time variables for these events:

$$t5 = t1 + t2 + t3 + t4 \quad [10.1]$$

$t1$  = detection time (s)

$t2$  = Fire Service notification time (s)

$t3$  = travel time to the incident (s)

$t4$  = access and search time (s)

$t5$  = attack commences (s)

An example of applying this relationship is based a single storey industrial building on the outskirts of a city's central business district, covered by automatic, monitored heat detectors. The alarm occurs during the business day, resulting in 30 staff being evacuated. The estimated response times are:

$$t1 = 1.6 \text{ mins} \quad t2 = 0.1 \text{ mins} \quad t3 = 8 \text{ mins} \quad t4 = 15 \text{ mins}$$

$$\therefore t5 = 24.7 \text{ mins}$$

#### **Detection and Notification Times**

These times can be estimated, especially if the building has an automatic detection system that transmits a signal to the Fire Service. A method is given in section 6.5 for detection time if people are expected to act as the sensors.

#### **Travel Time**

The Fire Service can provide estimates for the travel time to an incident. The maximum time for attendance to an urban fire in New Zealand is understood to be 8 minutes. The following table provides an estimate of response depending on risk classification [Bedford, 1993]:

Risk <sup>a</sup> Classification	Initial Response		Supporting Appliances	
	No. of Appliances	Attendance Times (mins)	No. of Appliances	Attendance <sup>b</sup> Times (mins)
High (1)	3	6 - 8	6	20
Normal (2)	2	8	2	20
Low (3)	1	8	2	30

Table 10.2 : Predetermined Fire Service Response

Notes: a: High Risk :

Buildings, or groups of buildings, located in urban areas which because of their size, construction, contents or processes, present a serious risk from fire, such as:

- high rise or large building complexes
- concentrated commercial, business and industrial areas
- large petrochemical processing plants and other hazardous areas
- wharf areas and associated shipping, warehouse and storage

## Normal Risk :

Buildings within urban areas that are not a high risk, such as:

- normal commercial, business and industrial areas which do not constitute a serious risk from fire
- detached and semi-detached residential property

## Low Risk :

Risks normally associated with small towns with a population of less than 1500 in principally rural areas, or sparsely populated urban areas on the fringes of large towns and cities.

b: The attendance time for supporting appliances is from the time of being called.

Requirements concerning physical access onto a site are covered under the NZ Building Code (Clause C3/AS1/2.17 ), and include:

- minimum access road load bearing capacity.
- all weather surfaces.
- minimum access route widths and clearances.
- maximum distances from buildings to access roads.
- access to Fire Service inlets, fire alarm panels and building entrances.

***Access and Search Times***

Search times should be controlled by most industrial buildings requiring a registered evacuation scheme, under the Fire Safety and Evacuation of Buildings Regulations (pursuant to s21A of the Fire Service Act). This is based on the assumption that most industrial buildings employ more than 10 staff and/or hold a dangerous goods licence.

The access and search times include verification of a fire, confirming that all occupants have evacuated and are accounted for, and establishing an attack position. Again the Fire Service could provide typical times. A conservative estimate for a building less than 10,000 m<sup>2</sup> is 15 minutes.

### ***Attack of Fire***

The effectiveness of an attack is limited by the available water supply, number of fire fighters, and access to the seat of the fire. Section 8 discusses the importance of effective smoke venting in limiting heat build-up, and facilitating access to the fire. An automatic, monitored alarm system is recommended for industrial buildings, and should be zoned in larger buildings to assist in identifying the fires location on the alarm panel. For single storey buildings with venting systems, this is can be verified through visual observation of where the smoke is issuing from the building.

The inclusion of an automatic sprinkler system obviously assists fire fighting operations through automatic notification, control of fire size, and identification of fire location. This form of protection provides the only probable means of controlling a fire before major damage can occur (also refer Section 7.2).

### ***Resources***

For mounting an attack on the fire, the extent of manpower and resources available needs to be clarified with the Fire Service during the design stage of a building. As discussed in Section 11, this issue is directly related to the size of the design fire and availability of water, and not to expected availability of Fire Service equipment. The possibility of simultaneous call-outs should not become a consideration; the clear expectations provided by the Fire Service Act should apply. All Fire Service equipment should be considered fully operational, in accordance with the Fire Service Act.

## **10.3 Risk Assessment**

The ability for the Fire Service to successfully respond to a fire relies on the success of the various conditional events. Reviewing the main events in terms of risk assessment [BRRTF, 1991]:

1. *Time and probability of detection and signal to the fire brigade by automatic or manual means,*
2. *Time and probability of brigade arrival at the building,*
3. *Time and probability of brigade set-up, and*
4. *Time and probability of successful fire brigade extinguishment.*

*The probability that set-up will be successfully completed and the brigade accomplishes extinguishment is the product of the probabilities of the above events.*

Each event is influenced by the physical environment and circumstances that could occur at the time of a fire. Typical parameters are [Fitzgerald, 1993]:

- a) Detection mechanism - automatic or manual?
  - reliability; maintenance, quality,
  - coverage, location of ignition source.
- b) Transmission signal - automatic system: reliability, type, completeness
  - manual system: human behaviour, location and access to telephone, reliability of transmission.
- c) Fire Service response - alarm handling time
  - simultaneous call out
  - travel time: weather, distance, obstacles
  - site access
- d) Fire Service set-up - building access
  - search and rescue time
  - fire location
  - water availability and supply characteristics
- e) Fire fighting - manpower available
  - equipment reliability
  - access to fire
  - fire size and energy

To account for the possible constraints on the Fire Service in the event of a fire, a risk assessment model can be completed. This will provide a probability of their successful attendance and extinguishment.

#### **Arrival and Set-Up Probabilities**

BBRTF [1991] provide estimated probabilities for arrival and set-up times:

Area	95 % Prob.		50 % Prob.	
	$(t_2+t_3)$ [s]	$t_4$ [s]	$(t_2+t_3)$ [s]	$t_4$ [s]
City	600	1200	300	600
Country	1200	900	600	450

Table 10.3 : Minimum Values for Fire Service Arrival and Set-Up



### Detection Probabilities

Sections 6.5 and 7.5 provide methods for calculating detection times. Maximum probability values for successful operation of automatic detectors are given below:

Component	Probability of Successful Operation		
	Smouldering	Non Flashover	Flashover
Sprinkler	0.05	0.97	0.99
Thermal Detector	0	0.90	0.95
Smoke Detector (single point)	0.65	0.75	0.75

Table 10.4 : Maximum Values for Probabilities for Automatic Detection

A probability of sprinkler activation after flashover suggests that the sprinklers would only be good for alarm notification. They would not be expected to control the fire.

For situations where there are no automatic detection systems, the probability that occupants will successfully respond to a fire cue and notify the fire service is given by the following equation [BRRTF, 1991]:

$$P[D] = P[\text{suitable cue for occupants to detect}] \times P[\text{occupants respond to the cue}] \times P[\text{fire service are successfully notified}]$$

$$\text{or } P[D] = P[Q] \times P[R] \times P[FS]$$

The following tables summarise the assessed probabilities. Note that  $P[FS]$  is taken to be 0.7:

Enclosure Description	Cue Type	P[Q]			P[R]
		Smouldering	Non-Flashover	Flashover	
Room of Origin	Visual/Olfactory	0.95	1.0	N/A	0 - 0.6
Adjacent Room	Auditory	0.0	0.3	0.4	0 - 0.6
	Olfactory	0.3	0.2	0.4	
Remote Room	Auditory	0.0	0.05	0.2	0 - 0.3
	Olfactory	0.1	0.05	0.2	

Table 10.5 : Maximum Values for Response Probabilities for Building Occupants

Note that  $P[R] = 0$  where the occupants are expected to be asleep. This is not an expectation within industrial buildings.

### ***Extinguishment***

The probability of the fire service successfully extinguishing a fire is dependant on the comparison between fire size versus the resources of the fire service. As discussed in Section 11, available water supplies and how they are applied play a major role in this equation. There is no reference on assessed probabilities for successful fire fighting action but a value of 0.95 is considered a reasonable estimate for the likelihood of the calculation technique being the actual outcome.

### ***Total Outcome***

The probability of a successful fire service action is therefore:

$$P[\text{Success}] = P[\text{Detect.}] \times P[\text{Arrival}] \times P[\text{Set-Up}] \times P[\text{Ext.}]$$

The remaining question is what is an acceptable success probability. Kersken-Bradley [1992] noted that *tolerable failure probabilities are generally specified by reference to comparable design situations and solutions, which are generally recognised as being safe*. This causes a problem in the current design environment, as there is no acceptable solution to make a comparison against.

The best outcome is to describe the expected fire service action in degrees of success, such as a high, medium-high, or low probability. The important point to be reiterated is that this design feature forms part of an overall fire safety strategy for a building, and the success of fire service action needs to be taken in the context of the complete fire protection system.

This includes achievement of the fire safety objectives, where successful fire service action may only be measured by their ability to control spread of fire to neighbouring properties.

## **10.4 Conclusions**

1. The critical factors in meeting New Zealand Building Code objectives is to ensure occupants evacuate safely and that the fire does not spread to neighbouring property.

2. The Fire Service has a clear legislative requirement to 'endeavour by all practicable means' to extinguish and prevent the spread of fire.
3. Effective Fire Service response relies on accessibility to adequate water supplies. The Fire Service Code of Practice for Fire Fighting Water Supplies identifies minimum supply requirements for various risk areas.
4. The overall performance of the Fire Service is reliant on the success of conditional events, such as fire detection and attendance times. These series of events can be expressed as probabilities, and Fire Service performance measured as a total probable event. There is, however, no design standard to gauge whether the predicted response of the Fire Service is acceptable.
5. Fire Service response is only one part of a fire safety strategy, and their expected performance needs to be considered in the context of a complete fire protection system.

## 11.0 FIRE FIGHTING DESIGN

This chapter aims to establish design methods that equate fire fighting capabilities with design fires within industrial buildings. Key areas considered are water resources, the cooling capacity of water, and the control of fire spread. Radiation to neighbouring property, and the benefits of prewetting adjacent buildings is also included in this review.

The section highlights the fact that in terms of property protection, the New Zealand Building Code only requires protection for neighbouring property. There is no requirement to protect owners' property from damage; although life safety measures can sometimes help in the restriction of internal fire spread. Section 4 also highlighted the owner's obligations to limit environmental damage in the event of a fire.

### 11.1 Cooling Power of Water

A number of parameters affect the quantity of water available for fire fighting:

- risk classification for the location of the site [as defined in the Code of Practice for Fire Fighting Water Supplies, refer Table 10.1].
- number of attending appliances and firefighters
- hose equipment used on the fire, and the volume of water per hose.
- application efficiency.

Bedford [1993] provided a table that summarised the resources expected to be committed to a fire, according to a fire zone. These zones are based on hose numbers and cross referenced to an earlier analysis carried out in the Macbar Fire Design Code [NZFPA, 1992]. The cooling capacity is established on the basis that 1 litre per second of water can absorb 2.605 MW of heat in converting water to steam, and that each hose supplies 15 l/s.

Fire Zone	Fire Engines (No.)	Hoses (No.)	Manpower (No.)	Water Flow (l/s)	Theoretical Cooling Capacity (MW)
1	3	4	12	60	156
2	5	8	20	120	312
3	8	12	32	180	468
4	10	16	40	240	624
5	13	20	52	300	780
6	15	24	60	360	936

Table 11.1 : Fire Engines and Manpower versus Cooling Capacity

Tables 10.2 and 11.1 can be used to assess the expected Fire Service response according to the associated risk. For most industrial complexes in urban environments, this means that 3 appliances are expected to attend to a fire call resulting in a water application rate of 60 lps, and a maximum cooling capacity of 156 MW. It should be expected that if attending appliances arrive at the scene of a significant fire (ie. where smoke is issuing from the building), then a second alarm would be raised and further appliances turned out.

### **11.1.1 Water Application Efficiency**

The effectiveness of the fire fighting water on a fire is very dependant on access to the fire for the water stream. In a small fire there is expected to be very good access that will allow effective wetting of the fuel and extinguishment of the flame through cooling and smothering.

For an established fire in an industrial building, access is usually difficult due to operations being based outside of the building. There is usually a lack of wall and roof openings (in relation to floor area), and the external walls are often on the site boundary with difficult access from the adjoining property. Skylights have begun to become a common feature in roof details, providing some opportunity for direct application of water into the fire compartment if they melt out. Water can also be directed towards neighbouring properties to reduce the risk of fire spread.

The maximum theoretical cooling capacity given in Table 11.1 does not allow for the inefficiency of water application onto a fire. The Macbar Fire Design Code [NZFPA, 1992] recommends a value of 32% but this assumes that the fire is 50% 'efficient'. The resulting effective application efficiency is 64%. Peet [1993] determined that for a case study involving a fire on the top level of a five storey commercial building, the application efficiency was 40% based on a comparison of the (estimated) total energy released versus the total cooling energy applied.

These application efficiency values reflect not only the cooling effect of water penetrating into the flaming zone, but also the cooling effect on the convective smoke plume and building fabric. The inefficiency occurs where water is misdirected or shielded from the fire zone.

In the calculations that follow, it is recommended that a cooling efficiency of 0.50 is used for the available water supply unless building features greatly improve the effective application of water. Suitable features would be a smoke ventilation system (refer Section 8), access from at least three sides, and low fire spread risk to neighbouring properties. Under these circumstances a cooling efficiency of 0.65 could be appropriate.

Amending Table 11.1 to account for the cooling efficiency values gives Table 11.2:

Fire Zone	Fire Engines (No.)	Water Flow (lps)	Theoretical Cooling Capacity (MW)	Cooling Capacity (MW) [eff. = 0.5]	Cooling Capacity (MW) [eff. = 0.65]
1	3	60	156	78	100
2	5	120	312	156	200
3	8	180	468	234	305
4	10	240	624	312	405
5	13	300	780	390	505
6	15	360	936	468	610

Table 11.2 : Cooling Capacity Based on Application Efficiency

Note that these recommended cooling efficiency values are based on limited referenced information and highlight the need for more detailed research.

### 11.1.2 Water Availability

If the design methodology for suppressing the fire is continued, the final step once the required water volume is calculated (based on design fire size, NZFS attack time, and cooling efficiency), is to confirm that this water flow rate is available. This returns the process to the responsibilities of the Fire Service under the NZ Fire Service Act.

Referring back to Table 10.1, the Water Supply Classification Table can be adjusted to indicate cooling capacity available according to the Territorial Authority's risk classification and assuming a cooling efficiency of 0.50. A designer should expect this minimum standard of water reticulation in the design area. If the actual supply is measured and found to be less, then the Territorial Authority or the Fire Service need to be advised. Note that occasionally the Territorial Authority has made a deliberate decision to not upgrade a reticulated supply, and a designer should not presume a minimum flow rate exists.

Risk Classification	NZFS Response	Minimum Water Flow Required (lps) (Reticulated)	Cooling Capacity Available (assuming cooling eff. = 0.50) MW
A	High	200	260
B	High	200	260
C	High - Normal	100	130
D	Normal	50	65
E	Normal - Low	25	32

Table 11.3 : Revised Water Supply Classification Table

If the available water supply is less than the cooling capacity required to suppress the fire and control fire spread to neighbouring property, then design amendments are required. Options are:

1. Install a sprinkler system.
2. Reduce the heat output by limiting the Fire Load Energy Density or reducing the firecell size.
3. Increase the fire resistance rating on the external walls causing exposure problems.
4. Increase the distance between the external walls causing the exposure problem, and the notional boundary.
5. Provide a reserve water supply.

## **11.2 Design Fire**

The design fire for a given industrial building should show a dynamic process. The resulting heat output will reflect the various stages of fire development (also refer Section 5):

- growth
- spread and (possible) flashover
- steady state, including venting effects
- decay

The fire development should involve the complete fuel load within the compartment unless its spread is controlled by sprinklers or other physical means such as fuel separation distances. Using a computer based fire simulation model such as CFAST (1992), an assessment of heat release rate and compartment temperatures can be assessed up to the time of roof collapse.

### **11.2.1 Heat Loss**

Alternatively, calculations can be applied to estimate the steady state heat release rate. Walton and Thomas (1993) viewed the conservation of energy for the upper gas layer in a compartment fire, as energy generated by the fire and added to the hot upper layer ( $Q_F$ ) equalling energy lost from the hot layer through radiation and convection plus the energy converted out the compartment openings ( $Q_L$ ). The following equations provide simplified methods for determining compartment heat loss based on boundary surface convection, radiation through unprotected openings, and convection from ventilation systems [Walton and Thomas, 1992, Drysdale, 1985]. Equations in section 5.0 and 8.0 can be used to establish compartment temperatures and smoke mass extraction rates.

a) Wall Convection  $Q_{CL} = A_w h_c \theta_w$  (kW) [11.1]

$A_w$  = Area of wall (m<sup>2</sup>)

$h_c$  = Convective heat transfer coefficient (kW/m<sup>2</sup>K)

$\theta_w$  = Temperature difference between upper gas layer and upper walls (K)

b) Radiation  $Q_{RL} = A_s \varepsilon \sigma (T_c^4 - T_a^4) \phi$  (kW) [11.2]

$A_s$  = Area of receiving surface (m<sup>2</sup>)

$\varepsilon$  = Emissivity (usually = 1.0)

$\sigma$  = Stephan Boltzmann constant [56.7 x 10<sup>-12</sup> kW/m<sup>2</sup>K]

$T_c$  = Temperature of fire compartment (K)

$T_a$  = Ambient temperature (K)

$\phi$  = Configuration factor; as follows [SANZ, 1988]:

Configuration factor for a rectangular source

$$\phi = \frac{2}{\pi} \left[ \frac{W}{\sqrt{(W^2 + 4D^2)}} \tan^{-1} \frac{H}{\sqrt{(W^2 + 4D^2)}} + \frac{H}{\sqrt{(H^2 + 4D^2)}} \tan^{-1} \frac{W}{\sqrt{(H^2 + 4D^2)}} \right] \quad [11.3]$$

Configuration factor for a circular source

$$\phi = \frac{R^2}{R^2 + D^2} \quad [11.4]$$

$W$  = width of source  
 $H$  = height of source  
 $D$  = distance between source and receiver  
 $R$  = radius of source

c) Ventilation  $Q_{VL} = M_e C_p \theta$  (kW) [11.5]

$M_e$  = Mass extraction rate (kg/s)

$C_p$  = Specific heat of air at  $[T_a + \theta]$  (kJ/kgK)

$\theta$  = Temperature difference between upper gas layer and ambient (K).

$\therefore$  Total Loss  $Q_L = Q_{CL} + Q_{RL} + Q_{VL} = Q_F$  [11.7]

Note that for a collapsed roof situation the mass extraction rate could equal the smoke mass flow rate for the fire. Refer Section 8 for effective mass flow rates from natural vents (ie. burnt out skylights).



### 11.3 Water Application versus Heat Output

Heat within a fire compartment perpetuates pyrolysis and combustion of flammable vapour. Applied water slows this process through heat transfer, oxygen depletion, blocking of re-radiation (smothering), and prewetting of adjacent fuels. These mechanisms vary according to the status of the fire (ie. growth stage, or following roof collapse), and the method of water application.

Equating cooling capacity with heat load becomes difficult to assess, given that a proportion of fire fighting water is 'misdirected' or shielded from the fire. This imbalance is reflected in the recommended cooling efficiency value of 0.5.

The following charts provide an example of how cooling capacity equates against heat output based on the typical heat release rate versus time relationship shown in figure 5.1. This charts show two scenarios:

- sufficient cooling water is applied to avoid roof collapse (fig. 11.1).
- insufficient cooling water is applied to avoid roof collapse, but the cooling lowers the effective heat release rate (fig 11.2).

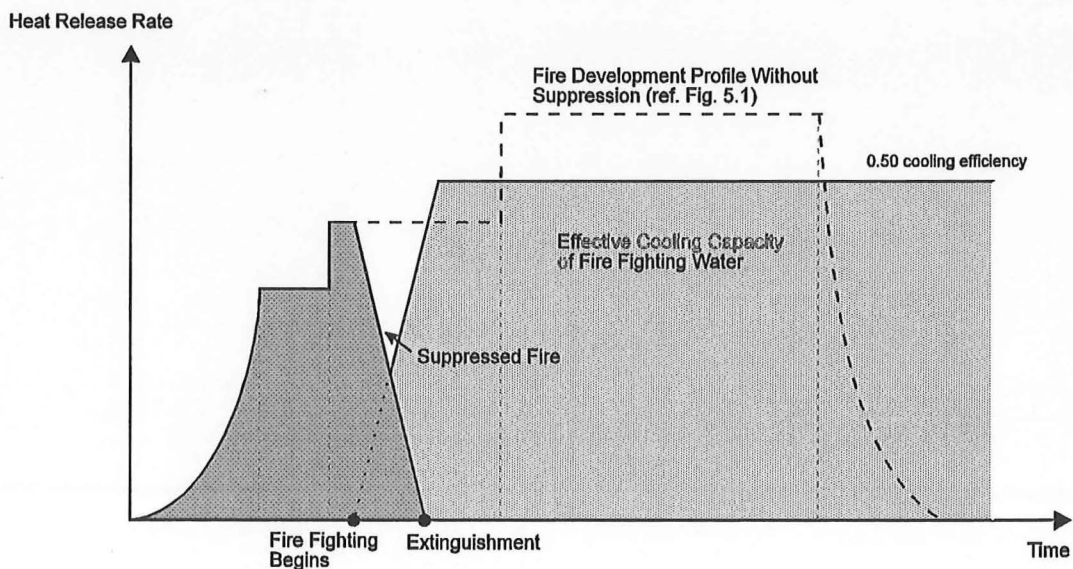


Fig. 11.1 : HRR versus Time Chart Showing Fire Fighting Water Extinguishing a Typical Fire Before Roof Collapse.

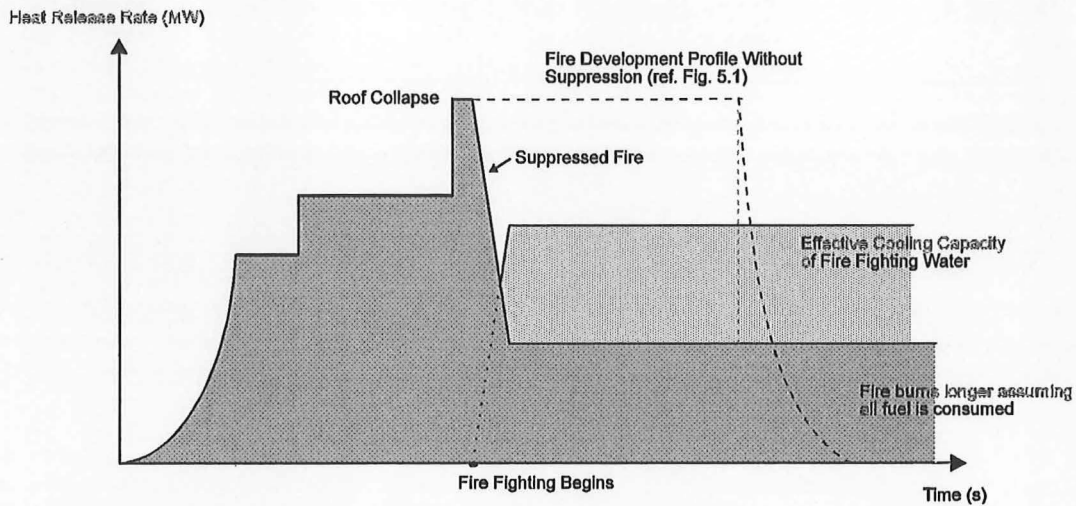


Fig. 11.2 : HRR versus Time Chart Showing Fire Fighting Water Extinguishing a Typical Fire After Roof Collapse.

### 11.3.1 Example

A warehouse storing PVC bottles has a potential maximum HRR of 450 MW. The site is located in a Class B urban area, with a High Risk classification, giving an initial Fire Service response of 3 appliances and then 5 supporting appliances. The water supply capacity is 200 lps.

The resulting effective cooling capacity of the water is:

$$\begin{aligned} \text{cooling efficiency} &= 0.5 \\ \therefore \text{max. cooling capacity available} &= 200 \text{ lps} \times 2.6 \text{ MW/lps} \times 0.5 \\ &= 260 \text{ MW} \end{aligned}$$

The Fire Service response equates to the following cooling capacity (also refer Table 11.2):

No. of Appliances	Water Flow (lps)	Cooling Power (MW) 0.5 Efficiency
3 (initial)	60	78
5 (supporting)	120	156
8 total	180	234

The total demand is within the supply available from the street supply. The maximum expected cooling power of 234 MW is less than the maximum expected heat release rate of 450 MW, and therefore the fire is expected to be suppressed but not extinguished. A typical heat release rate versus time chart is shown below:

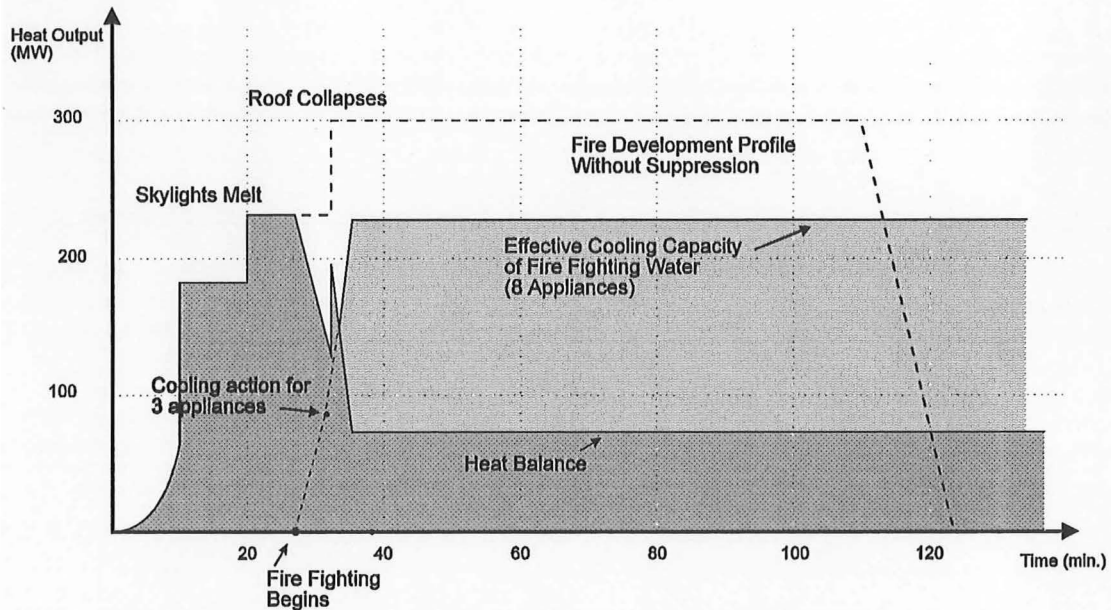


Fig 11.3 : Suppression of Fire Using Fire Fighting Water - Worked Example

Figure 11.3 has assumed a fire development profile, including the onset of roof collapse even though there is a reduction in the net heat output due to water cooling.

If the effective cooling capacity from fire fighting action is greater than the effective heat release rate, then the design fire is considered able to be extinguished. Alternatively if the analysis concludes that the effective cooling capacity is less than the design heat release rate then the fire is considered to only be suppressed.

This approach is quite simplistic and does not adequately represent problems in completely extinguishing a major fire, but it does indicate how water can be used to effect extinguishment or suppression.

The NZ Building Code, however, only requires protection for the neighbouring property. Less water is necessary to achieve this objective, although it also follows that if extinguishment of the design fire occurs then the fire will not spread to the neighbouring property.

An alternative design approach is to ensure that the Fire Service at least controls the spread of fire by cooling boundary walls. On this basis the building contents can burn until extinguishment finally occurs or the fuel burns out.

## 11.4 Prewetting Neighbouring Buildings

The radiation risk to neighbouring buildings can be calculated using equations given in Section 5.5. Factors that influence the radiation risk to neighbouring properties include separation distance, radiation emission, and the construction of the receiving surface

This last factor is very important as industrial properties are not expected to have *non-fire rated* walls unless they are at least 3-4 m away from the site boundary. As shown in Table 5.1 non-combustible walls require at least 50 kW/m<sup>2</sup> radiation intensity and include fire rated glazing, before possible ignition of the contents behind the fire rated glazing, given there is pilot ignition. This is 4 times the minimum level for wood surfaces. The NZ Building Code Acceptable Solutions (1991) do allow walls to have combustible surface finishes if they are greater than 1 m away from the boundary, but this is not expected to undermine the performance of a fire rated structure, only increase vertical fire spread risk.

If the Fire Service perceive a spread of fire risk to neighbouring property they will douse the facing wall surfaces. This raises the critical radiation intensity significantly due to the ability for water to absorb heat.

The following example highlights a design process for determining expected radiation intensity on an adjacent property, using a choice of equations 5.17 - 5.19. From applying 1 l/s of water over the receiving face an effective total cooling power of 2.6 MW is provided. This can then be reduced to a kW per m<sup>2</sup> figure and added to the critical intensity value for the receiving surface, to raise the minimum pilot ignition radiation intensity. This simple analysis assumes that there is continuous water application over the entire surface. Similarly to water application onto the fire, there needs to be an application efficiency to account for erratic application; a suggested value is 0.25 given the increased difficulty in directing water streams.

### 11.4.1 Example

A 150 MW fire is occurring within a plastics factory. Flames are issuing above the wall line and providing a spread of fire risk to a neighbouring building constructed from timber. The distance between the flame point source and the neighbouring wall (measuring 20m x 3m high), is 6m at an angle of 45°. What is the radiant heat flux on the surface, and how does the critical radiation intensity change if 1 lps and 30 lps water is applied over the entire neighbouring wall surface?

- a) Radiant heat flux - assume a point source [eqn. 11.8]

$$Q_R = (0.3 \times 150 \cdot \cos 45^\circ) / 4 \cdot \pi \cdot 6^2$$

$$= 70 \text{ kW/m}^2$$

Critical radiation intensity (from Table 11.4) =  $16.7 \text{ kW/m}^2$

$\therefore$  ignition likely to occur

- b) Cooling power of 1 lps water over surface =  $(2.6 \text{ MW} / 60 \text{ m}^2) \times 0.25$  application efficiency.

$\Rightarrow 10.8 \text{ kW/m}^2$ . This would still lead to probable ignition as the net heat radiation is  $[70 - 10.8] 59.2 \text{ kW/m}^2$  (ie.  $> 16.7 \text{ kW/m}^2$ ).

- c) Assume 30 l/s applied from two hoses (total) over the surface:

$$\begin{aligned} &= (2.6 \text{ MW} \times 30 \text{ l/s}) \times 0.25 / 60 \text{ m}^2 \\ &= 325 \text{ kW/m}^2 \text{ cooling power} \end{aligned}$$

$\Rightarrow$  clearly exceeds the  $70 \text{ kW/m}^2$  incident radiation, and therefore the risk is contained.

This example highlights how little volume flow of water is required to control spread of fire to neighbouring properties. One hose line should be able to provide 10 -15 lps water and as long as the complete wall (in the example) could be constantly doused there should not be a risk of fire spread. As discussed, neighbouring walls of *combustible* construction in industrial zone areas will have a minimal 3-4 m separation distance from the boundary, depending on their facing dimensions. This should allow sufficient distance to apply a complete water spray in most cases.

## 11.5 Conclusions

1. The NZ Building Code requires protection for neighbouring property only. There is no requirement to protect owners property from damage although an owner may need to control the effects of a fire on the environment to comply with the Resource Management Act and Building Act.
2. If the effective cooling capacity available from fire fighting water is greater than the effective heat release rate, then the design fire is considered able to be extinguished. Alternatively if the analysis concludes that the effective cooling capacity is less, then the fire is considered to only be suppressed.
3. Suppressing or extinguishing an industrial building fire is dependant on the ability to direct water into the fire. The recommended application efficiency is 0.50, and increased to 0.65 if the building features greatly improve the

effective application of water. These values are based on limited reference material and this area requires more research.

4. Fire fighting response is limited by the available water supply. A designer needs to confirm the site supply and amend the fire safety design to match cooling power against the spread of fire risk.
5. The quantity of water required to control fire spread to neighbouring property is expected to be much less than the quantity required for fire control. Prewetting neighbouring property is a very effective method of limiting fire spread.

## 12.0 CONCLUSIONS AND RECOMMENDATIONS

### 12.1 *Introduction*

This document aims to establish a design methodology for meeting basic fire safety objectives within single storey industrial buildings using a 'common-sense' approach. It is recognised that further research is required to substantiate design factors used, and that fire engineering design for single storey industrial buildings needs to be treated apart from other building types. Reviewing the main conclusions:

### 12.2 *Statistical Research*

#### 12.2.1 Literature Survey

A literature survey was completed to assess fire incident trends from other countries. The main conclusions were:

- 2.1 High fire load incidents typically accounted for 15% of fires studied, and 50% of the loss.
- 2.2 Fire load density is probably the most important factor for the fire growth and extent of damage.
- 2.3 The likelihood of warehouse fires was considerably higher than fires in the process and manufacturing industry.
- 2.4 A warehouse fire is likely to occur in a particular warehouse once every hundred years [ $p(\text{reportable fire}) = 1.2 \times 10^{-2} \text{ year}^{-1}$ ]
- 2.5 The probability of a 'serious' warehouse fire occurring in a particular warehouse, is between  $2.5 \times 10^{-3}$  and  $5.5 \times 10^{-3} \text{ year}^{-1}$ . A serious fire included all fires where roof collapse occurred.
- 2.6 Serious warehouse/storage fires not only result in extensive damage to structures and contents, but also present a significant risk to the environment.
- 2.7 The majority of fires (62%) occur between 6pm and 6am, when the premises are presumably unmanned or only a minimal number of staff are present.

### **12.2.2 NZFS Incident Records**

A review was carried out on New Zealand Fire Service incident statistics for manufacturing and warehousing facilities, between the years 1988 and 1994. The aim was to identify high and low risk factors associated with recent fires, and recommend improvements to reduce the incidence of serious fires.

The main recommendations from this review and the literature survey are:

- 2.1 Automatic detection systems should be included in industrial buildings, especially businesses associated with wood and paper products.
- 2.2 To minimise unlawful entry, security systems should form part of the fire safety management programme.
- 2.3 Periodic risk assessments need to be undertaken to ensure that the correct level of protection and hazard management is occurring to suit the risk and fire safety strategy.

The conclusions from the statistical research were used to help develop the direction in the overall research project.

## **12.3 *Fire Safety Management***

The fundamental concept with fire safety management is loss control, or to minimise both the chance and consequences of a serious fire. Loss control is not only important during a buildings design phase, but also once the business is operational. The objective of this section was to highlight appropriate fire safety management techniques, and reinforce the need for fire safety to be continually reviewed and reinforced.

### **12.3.1 Design Process**

The design process begins with ensuring the safety of occupants in the event of a fire. A fire engineer needs to also highlight to a property owner, the added risks to property and operations. A fire safety strategy can then be developed. Main conclusions are:

- 3.1 Current regulatory requirements do not address property and business loss control (for the owner); only life safety, spread of fire, and environmental protection issues.



- 3.2 Loss control should be reinforced during the design process. This requires determination of acceptable loss, and application of risk assessment and cost/benefit techniques.

### **12.3.2 Existing Operation**

An on-going fire safety management programme should be introduced that incorporates:

- Fire prevention training and audits.
- Evacuation systems.
- Pre-incident plans.

This ensures that fire safety and loss control does not diminish during the use of a building. Main conclusions are:

- 3.3 Owners of industrial buildings need to develop a culture that accepts fire prevention training and audits as part of the business plan. Exercises should be held on an annual basis.
- 3.4 An approved evacuation system should be established and maintained for occupied buildings in accordance with the Fire Safety and Evacuation of Buildings Regulations (1991).
- 3.5 Pre-incident planning should be encouraged to ensure that responding personnel can effectively manage incidents with available resources.
- 3.6 Contingency plans need to be in place to minimise disruption to the operation of the business in an emergency.

## **12.4 Environmental Protection**

The design of industrial buildings should not only consider the effects of fire within the immediate site area, but also the possible effects to the greater environment. The New Zealand Resource Management Act 1991, requires any development proposals to assess the effect that the development would have on the environment, and to either eliminate, isolate or control possible hazards.

The Building Act 1991 also places a responsibility on a building owner to protect the environment from any event originating within a building operation. However, in contrast to other building control issues, the NZ Building Code gives inadequate guidance on acceptable design for controlling environmental hazards.

The main conclusions from this review are:

- 4.1 There is a clear need to provide acceptance criteria for hazardous processes and their containment under fire conditions to safeguard the environment.
- 4.2 Plant design for sites containing 'significant' hazardous substances should include risk assessment, and result in safety controls to suit the risk.
- 4.3 The ideal solution is to control or extinguish the fire before any pollution occurs. Automatic extinguishment systems such as sprinklers protection can assist in minimising both air and water pollution.
- 4.4 Bunding or containment reservoirs are an important environmental safety feature. The design is dependant on the quantity of goods held and the volume of fire fighting water expected to be applied.
- 4.5 Auditing, trial emergency procedures, and familiarisation by outside authorities need to become part of the industry culture. The scale of an industrial fire is often underestimated.

## **12.5 Fire Design Procedure**

A fire design procedure should identify the variables that can affect the outcome of a fire, such as fuel layout and Fire Service response, and predict the main stages of fire development, including:

- fire growth
- fire spread within the firecell
- open air burning following roof collapse
- boundary exposure

The main intent of a fire design procedure and modelling fire behaviour, is to assist in the following

- 5.1 Determination of the risk to life safety and risk of fire spread to adjacent property.
- 5.2 Assessment of the benefits of enhanced active and passive fire protection to minimise these risks.

Important features associated with a fire development procedure are:

- 5.3 Provision of adequate information on the combustible contents, the building design, and the fire protection features.

- 5.4 Development of a time/HRR graph for use in determining structural failure conditions, boundary exposure, and the effect of Fire Service response.
- 5.5 Radiant heat flux calculations to assess the risk of fire spread to neighbouring property, and determine the effect that prewetting has on lowering the risk.

If the intended building use is not known then the prescriptive solution in the NZBC can be adopted.

## **12.6 Life Safety**

The objective in life safety design is to ensure that building occupants either escape, are rescued or find a place of refuge before untenable conditions occur, and that Fire Service personnel are adequately protected to undertake rescue operations. Conclusions from this section are:

- 6.1 Occupants within industrial occupancies are expected to be alert, active and mobile, plus familiar with their surroundings.
- 6.2 One method of designing a suitable escape system is applying a prescriptive solution. These are based on conservative travel speeds, exit configurations and untenability conditions.
- 6.3 The recommended design method uses deterministic and behavioural models to compare estimated evacuation time ( $T_{ae}$ ) against the untenability time ( $T_u$ ). The escape route design must prove that  $T_{ae}$  is less than  $T_u$ , otherwise improvements are required.
- 6.4 Automatic detection/suppression systems reduce evacuation times as well as improving the likelihood of controlling the fire. They are recommended for inclusion in industrial buildings.

## **12.7 Sprinkler and Detection Systems**

The aim of this section was to promote the advantages of automatic fire protection and outline appropriate systems for single storey industrial buildings. Emphasis is given to firstly establishing a fire safety strategy, then designing systems to suit. Conclusions are:

- 7.1 System goals for a site fire safety strategy can be placed in three categories: life safety, property protection, and business protection.
- 7.2 To determine the most effective fire safety strategy in terms of cost and performance, a site fire risk assessment should be completed.

- 7.3 The minimum level of fire protection expected for a single storey industrial building for life safety purposes is a manual call point and alarm system. Inclusion of automatic detection or suppression systems enhances life safety, and should be incorporated in building design wherever possible.
- 7.4 Fire safety designs relying on detector performance, must account for the detector RTI, activation temperature, and the transport time lag.
- 7.5 Sprinklers are the only expected method of controlling a fire within a typical industrial complex. The Fire Service cannot be expected to attack and suppress a fire from receiving an alarm call without sprinkler support.
- 7.6 A critical part of sprinkler design is establishing the correct hazard classification. This evaluation should form part of the initial risk assessment.

## **12.8 Roof Venting**

The objective of this section was to provide a design method for the sizing and operation of roof vents in industrial buildings. Roof vents provide smoke control within a compartment, and assist with escape systems, fire fighter operations, and limitation of damage during the initial stages of a fire. Conclusions are:

- 8.1 A roof venting system should form part of a fire design strategy. It is not a substitute for sprinklers or other extinguishing systems.
- 8.2 Roof vents can be provided by natural vents or mechanical extraction. Both forms rely on the buoyancy pressure of the fire to drive the smoke outside.
- 8.3 Sprinklers operating without roof vents are expected to control the fire, but cause greater smoke and water damage.
- 8.4 Sprinklers and roof vents should be integrated where possible. Sprinklers are recommended to operate first, with roof vents minimising smoke damage and assisting Fire Service operations.

## **12.9 Structural Performance**

One of the primary objectives in fire safety design is to control the spread of fire. For limiting fire spread to adjacent properties, boundary walls become the most important structural feature, where these in turn are dependant on the primary support design. The objective of this section was to recommend a suitable

technique for designing external boundary walls, with due regard to the 'S' rating system, the primary support system, and the preferred failure mechanism.

- 9.1 To reduce the probability of fire spread to neighbouring property from fire in unsprinklered buildings with  $FLED > 1500 \text{ MJ/m}^2$ , walls close to boundaries should be provided with a fire resistance rating of 4 hours.
- 9.2 This rating can be reduced if it is proven that either the design fire, separation distance or building design will result in a reduced exposure risk.
- 9.3 If the fire resistance rating provided is less than the severity of the expected fire, the assistance of the Fire Service will be required to prevent fire spread to neighbouring property.
- 9.4 Using equivalent time formulae is considered conservative due to no allowance for reduced fire severity for open air fires and expected Fire Service response.
- 9.5 The critical elements in the boundary wall design are the connections between the panels and support structure, and between adjacent panels. These need to be designed to ensure that the walls function as one unit, and do not collapse outwards during a fire.

## **12.10 Fire Service Intervention**

The Fire Service has a clear legislative requirement to 'endeavour by all practicable means' to extinguish and prevent the spread of fire. Their success in reaching this goal is dependant on conditional events such as attendance times, rescue operations, and securing of sufficient water supplies. The aim of this section was to highlight Fire Service responsibilities, capabilities and constraints. Conclusions are:

- 10.1 The critical factors in meeting NZBC objectives is to ensure occupants evacuate safely and that the fire does not spread to neighbouring property.
- 10.2 Effective Fire Service response relies on accessibility to adequate water supplies. The Fire Service Code of Practice for Fire Fighting Water Supplies identifies minimum supply requirements for various risk areas.
- 10.3 The overall performance of the Fire Service is reliant on the success of conditional events, such as fire detection and attendance times. These events can be expressed as probabilities, and Fire Service performance measured as a total probable event. There is, however, no design standard to gauge whether the predicted response of the Fire Service is acceptable.

- 10.4 Fire Service response needs to be considered as part of the overall fire safety strategy for the building.

### **12.11 Fire Fighting Design**

The aim of this section was to establish a design method equating fire fighting capabilities with design fires for industrial buildings. Important parameters in this equation include water resources, the cooling capacity of water, and the control of fire spread. Conclusions are:

- 11.1 If the effective cooling capacity available from fire fighting water is greater than the effective heat release rate, then the design fire is considered able to be extinguished. Alternatively if effective cooling capacity is less, then the fire is considered to only be suppressed.
- 11.2 Fire fighting response is limited by the available water supply. A designer needs to confirm the site supply and amend the fire safety design to match cooling power against the spread of fire risk.
- 11.3 Suppressing or extinguishing an industrial building fire is dependant on the ability to direct water into the fire. The recommended application efficiency is 0.50, and increased to 0.65 if the building features greatly improve the effective application of water. These values are based on limited reference material and this area requires more research.
- 11.4 The quantity of water required to control fire spread to neighbouring property is expected to be much less than the quantity required for fire control. Prewetting neighbouring property is a very effective method of limiting fire spread.

### **12.12 Future Research**

Recommended areas for future research include:

- 12.1 Modelling spread of fire between large combustible surfaces, such as racks.
- 12.2 Improving the techniques for estimating reaction and preparation times in the estimated evacuation (behavioural) time equation.
- 12.3 Establishing application efficiencies for fire fighting water on building fires.
- 12.4 Determining the effectiveness of prewetting on unburnt combustibles with respect to reduction in critical radiation intensity.

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School of Engineering  
University of Canterbury  
Private Bag 4800, Christchurch, New Zealand

Phone 643 366-7001  
Fax 643 364-2758